MMs: Metamaterials; MEMS: Microelectromechanical Systems; THz: Terahertz Technology

MEMS and Metamaterials: A Perfect Marriage at Terahertz Frequencies

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14. ABSTRACT

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RHM vs. LHM

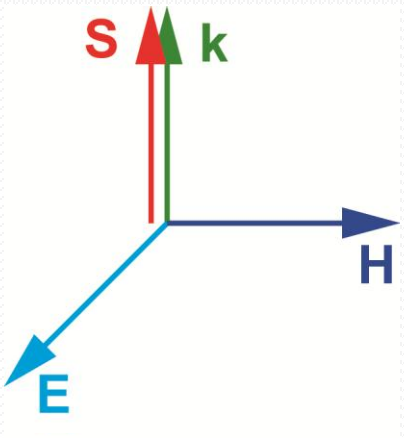
Use Maxwell equations to describe the electromagnetic behavior of the materials:

$$\mathbf{k} \times \mathbf{E} = \omega\mu\mathbf{H}$$
$$\mathbf{k} \times \mathbf{H} = -\omega\varepsilon\mathbf{E}$$

and $\mathbf{S} = \mathbf{E} \times \mathbf{H}$

ε: Permittvity; μ: Permeability

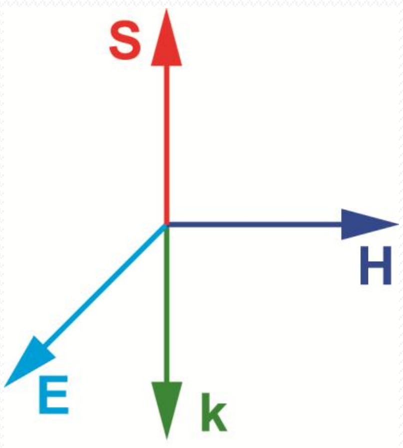
<u>ε>0, μ>0:</u> **E, H, k** *right* handed



- $\mathbf{S} \uparrow\uparrow \mathbf{k}$
- $\mathbf{v}_{\text{group}} \uparrow\uparrow \mathbf{v}_{\text{phase}}$

The direction of wave propagation is the same as the direction of energy flow.

<u>ε<0, μ<0:</u> **E, H, k** *left* handed



- $\mathbf{S} \uparrow\downarrow \mathbf{k}$
- $\mathbf{v}_{\text{group}} \uparrow\downarrow \mathbf{v}_{\text{phase}}$

The directions of wave propagation and energy flow are opposite.

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What is Metamaterial: Overview

Definition:

$$n^2 = \frac{\varepsilon\mu}{\varepsilon_0\mu_0}$$

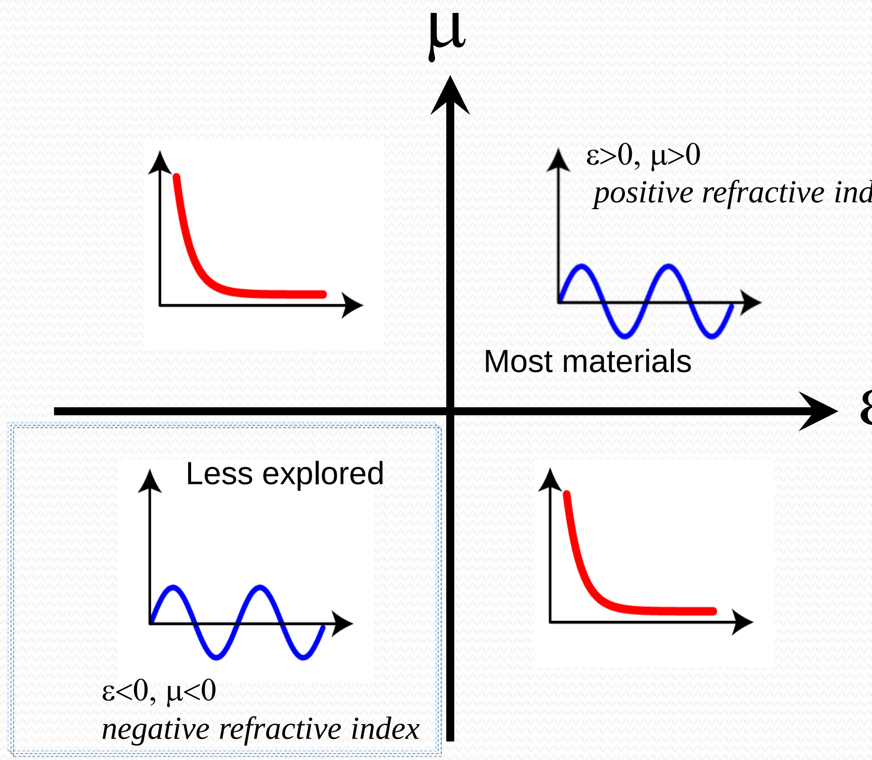
$$k^2 = \omega^2\varepsilon\mu$$

n: refractive index

- ε>0, μ>0: $\Rightarrow n^2, k^2 > 0$
  propagating wave
  positive refractive index

- ε>0, μ<0: or ε<0, μ>0 $\Rightarrow$
  $n^2, k^2 < 0$
  evanescent wave

- ε<0, μ<0: $\Rightarrow n^2, k^2 > 0$
  propagating wave
  negative refractive index



Right handed materials:

$$n = \sqrt{\frac{\varepsilon\mu}{\varepsilon_0\mu_0}}$$

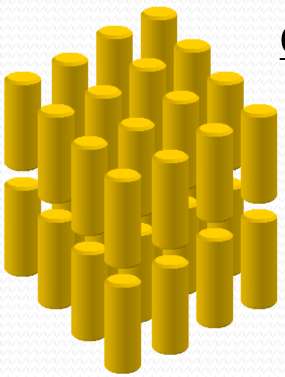
Left handed materials:

$$n = -\sqrt{\frac{\varepsilon\mu}{\varepsilon_0\mu_0}}$$

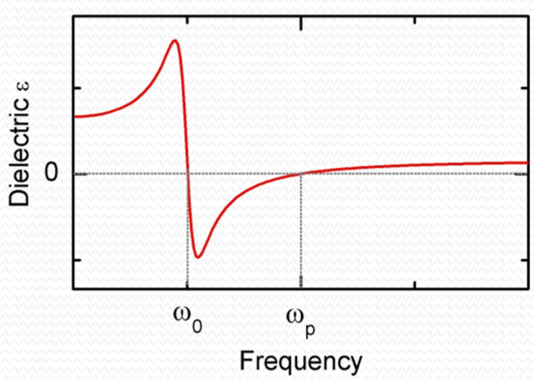
Metamaterials

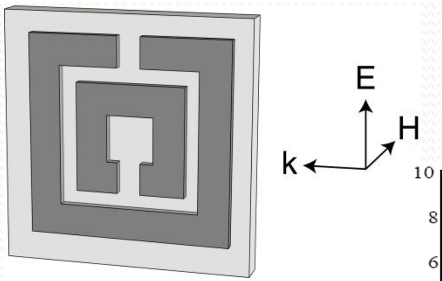
Artificial structured materials with controllable electromagnetic properties (ε, μ, n, …) at desired frequency.

- ε < 0: Cut wire structured plasma (negative permittivity)
- μ < 0: Split-ring resonators (negative permeability)
- n < 0: Composite metamaterials (no existing natural material with both ε and μ at the same frequency)

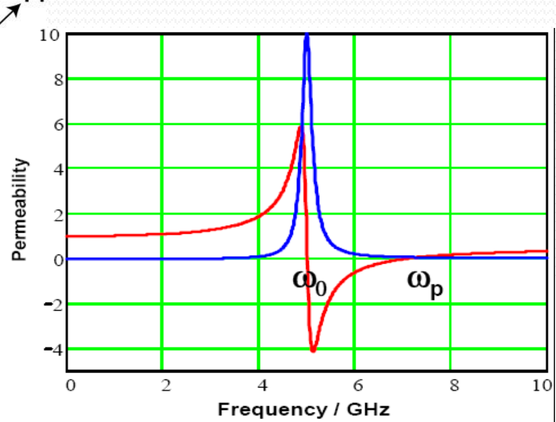


Cut wire structured plasma

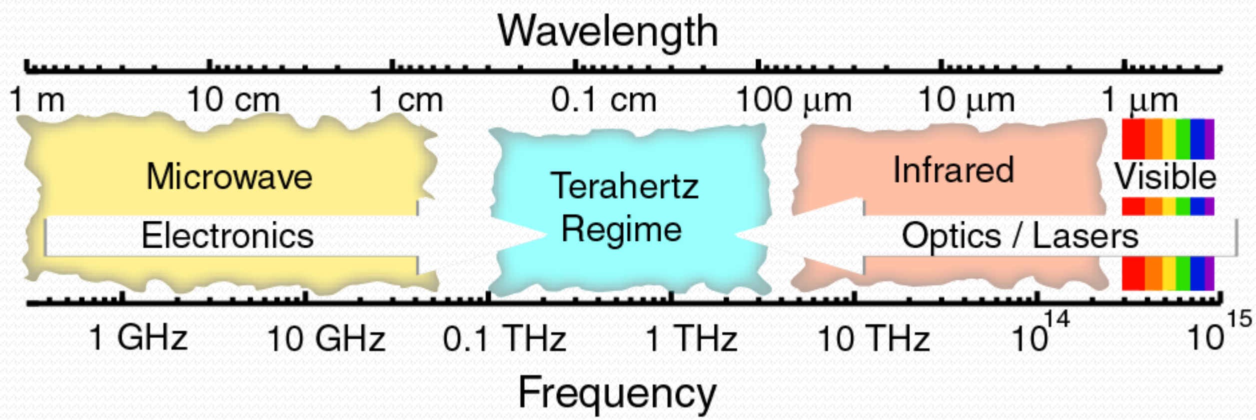




Split-ring resonators



"Terahertz Gap"



Microwave: electron

<u>Electronics:</u> Antenna, high speed transistor circuits for microwave generation, detection, control and manipulation

<u>Applications:</u> Wireless communications, radar…

Terahertz gap

Moderate progress in sources and detectors, functional devices such as filters, switches, modulators largely do not exist;

Practical applications are limited.

1 THz → 300 μm → 4 meV → 33cm^{-1} → 47 K

Infrared and visible: photon

<u>Photonics:</u>

Source: Lasers, LEDs

Detector: Photodiodes

Functional: Lens, polarizer, optical switch

<u>Applications:</u> Optical fiber communications…

The term terahertz gap refers to the lack of emitters/sources and detectors in the spectrum. Neither traditional optical nor microwave techniques work well in the THz region, and new methods/materials have yet to be explored.

Wish List

- Higher power source;
- More sensitive and cheaper detectors;
- Compact way to tune/modulate the radiation.

Metamaterials

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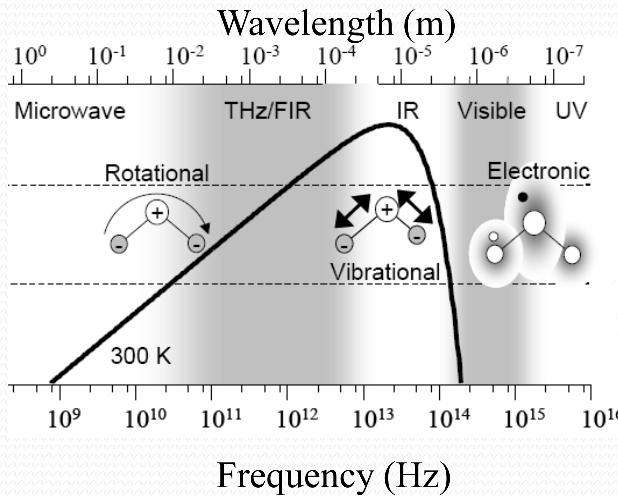
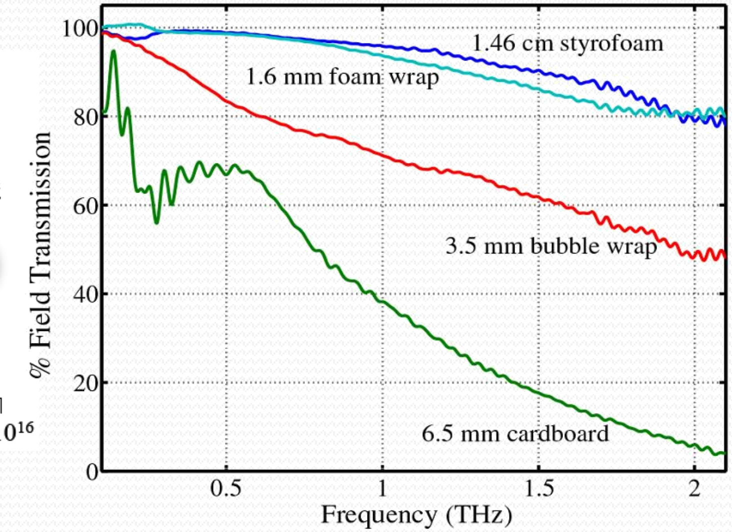
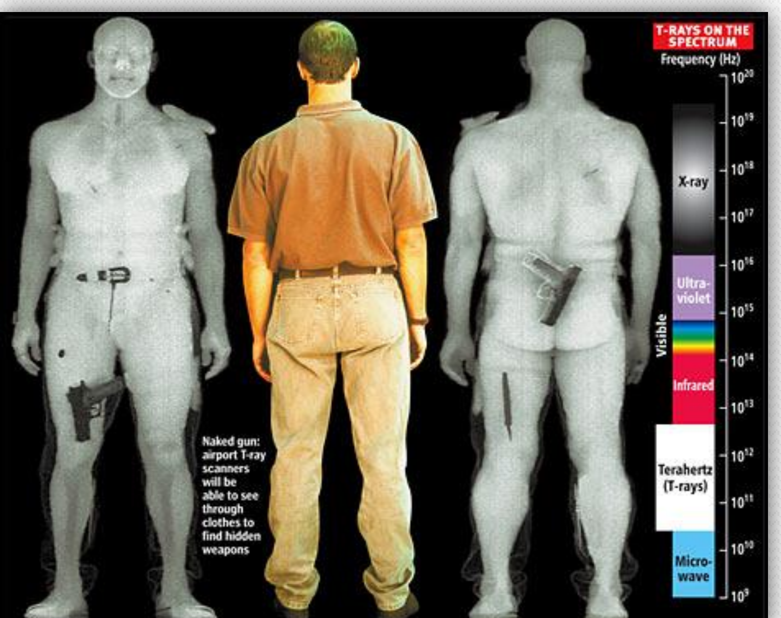
Why Terahertz?





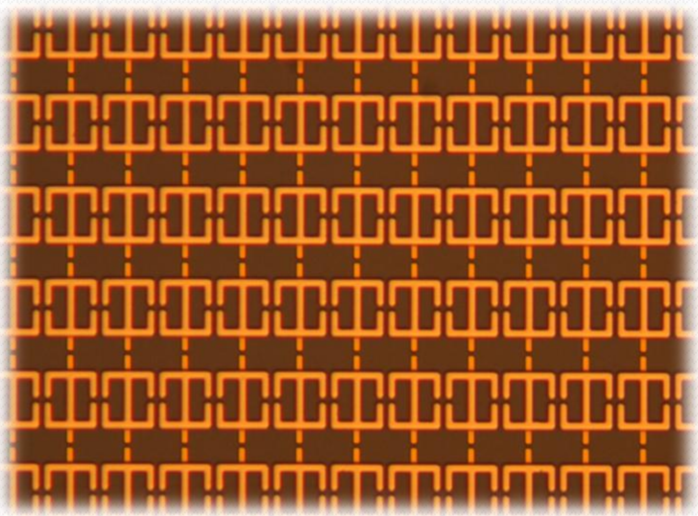


- THz radiation is non-ionizing, safe to use on humans;
- Could penetrate many visually opaque materials such as clothing, paper, cardboard, wood, plastic, ceramics, useful to safety scanning;
- Vibration and rotation molecular excitation for simultaneously investigation of both physical and chemical properties of a material.

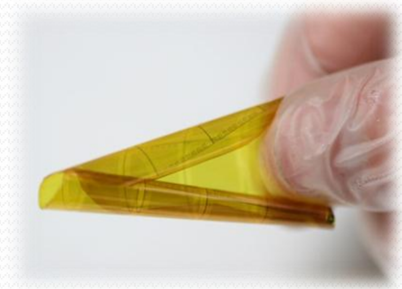
- Chemical/biological agents detection
- Ultrafast communications;
- Screening for security;
- Biological imaging;

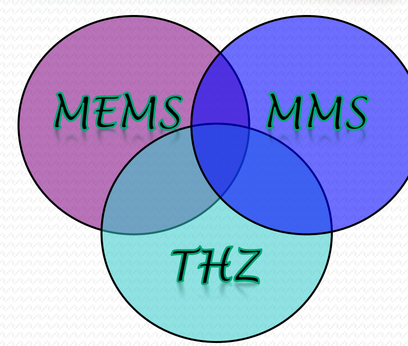
Terahertz Metamaterials

- A metamaterial unit cell is to terahertz wave, as an atom is to visible light
- Metamaterials can be easily tuned to desired electromagnetic properties (much easier than finding the right natural material)
- Size of terahertz metamaterials is a perfect match for microfabrication techniques



Flexible, active, dynamic, 3D,…





MEMS & Metamaterials: A perfect marriage at THz frequencies

- Metamaterials are sub-wavelength structures in array form.
- 1 Terahertz corresponds to 300 microns.
- Sub-wavelength of terahertz is around tens of micron.
- MEMS is a very powerful tool in terms of fabrication.

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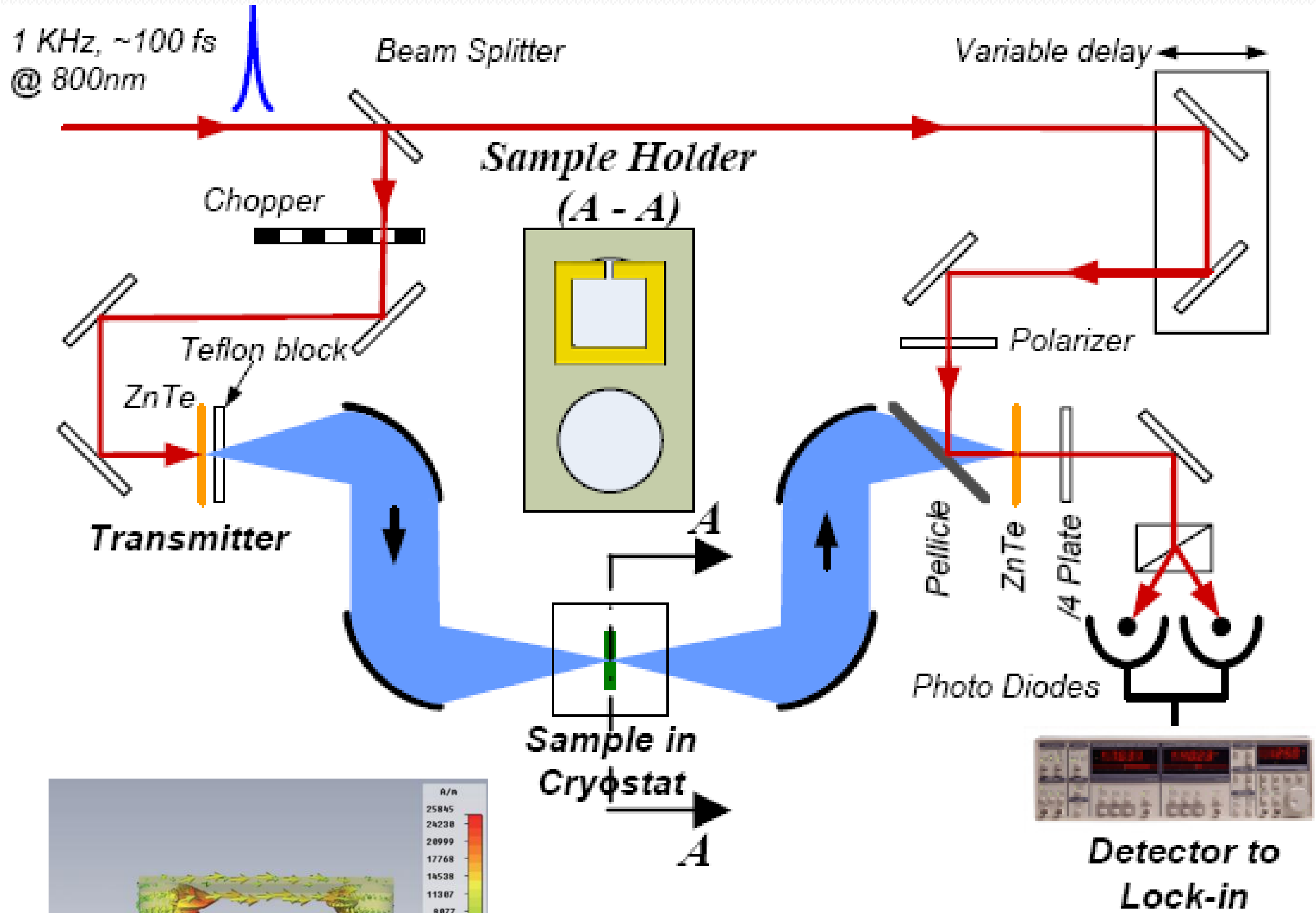
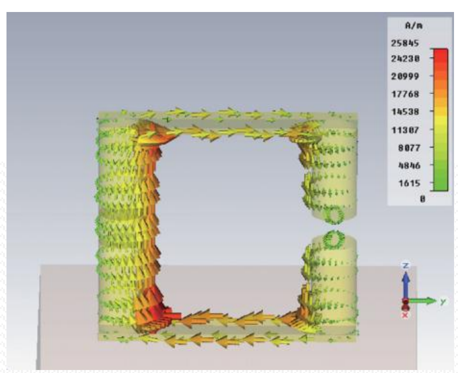
THz TDS (Time Domain Spectroscopy)

We use terahertz time domain spectroscopy to characterize our samples.

We have a femto-second laser pulse to excite the optical crystal to get our terahertz radiation and then we focus the terahertz pulse onto our sample, and then we measure the sample response in the time domain.

By using Fourier Transform, we can get the response at frequency domain.





Simulated circulating surface current density at the fundamental resonance

To better understand the resonant properties at the fundamental resonance, numerical simulations are conducted using full wave EM simulations with CST Microwave StudioTM 2009

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Single planar metamaterials on GaAs substrate

THz wallpaper metamaterilas with multiple resonances

Metamaterilas in ultrathin silicon nitride substrates

Flexible metamaterials at terahertz frequencies

Metamaterials on paper as a sensing platform

Silk metamaterilas at terahertz frequencies

THz metamaterial 'perfect' absorbers (flexible, wide angle, dual band)

Tunable metamaterials at terahertz frequencies (frequency, structurally)

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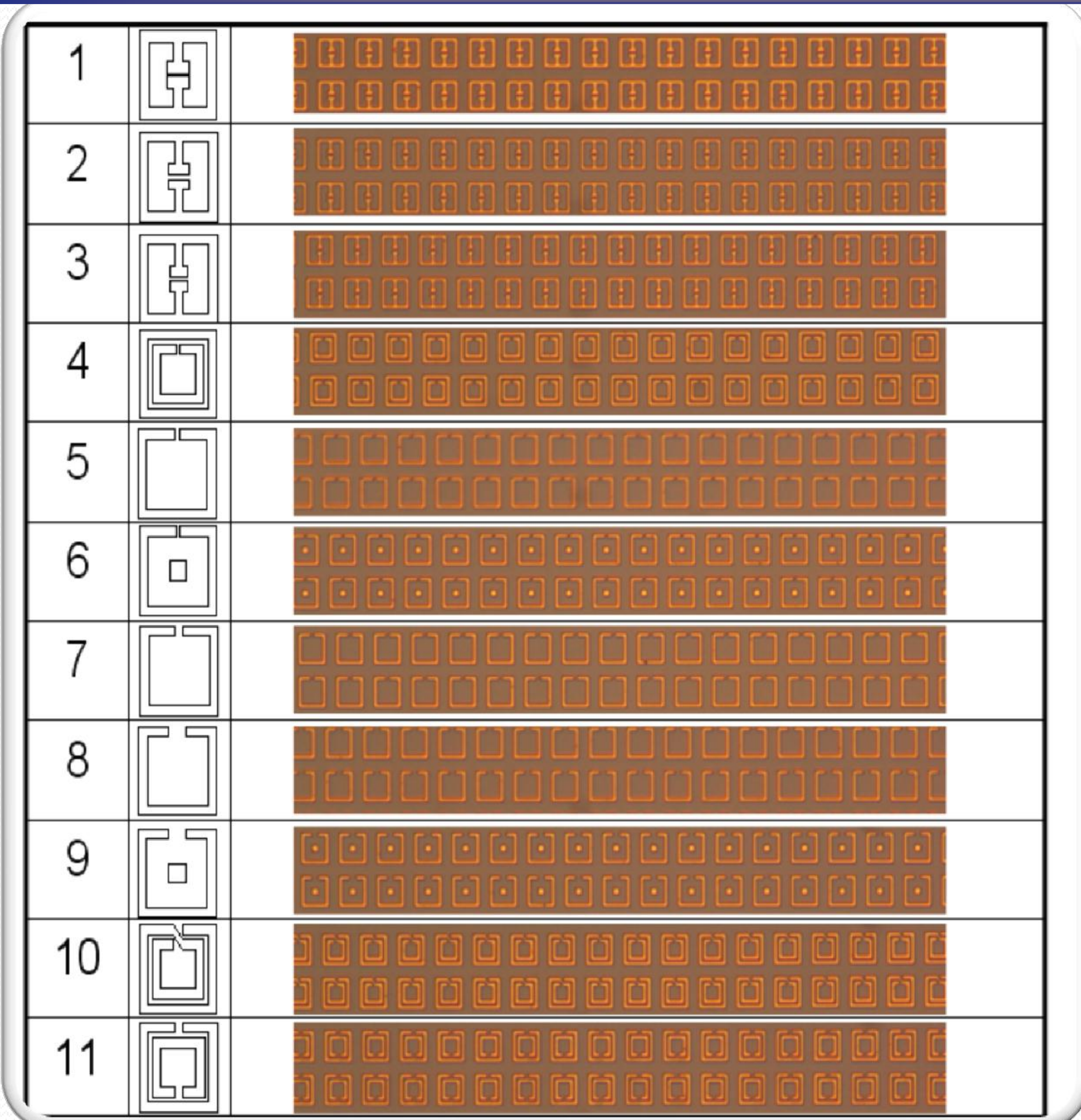
Single Planar Metamaterials on GaAs Substrate



- Planar metamaterial arrays fabricated consist of 200 nm thick Au split ring resonators (SRRs) fabricated on GaAs substrates.

- Semi-insulating GaAs wafers were chosen because they are highly transmitting at terahertz frequencies.

Optics Express, 16 (23), 2008

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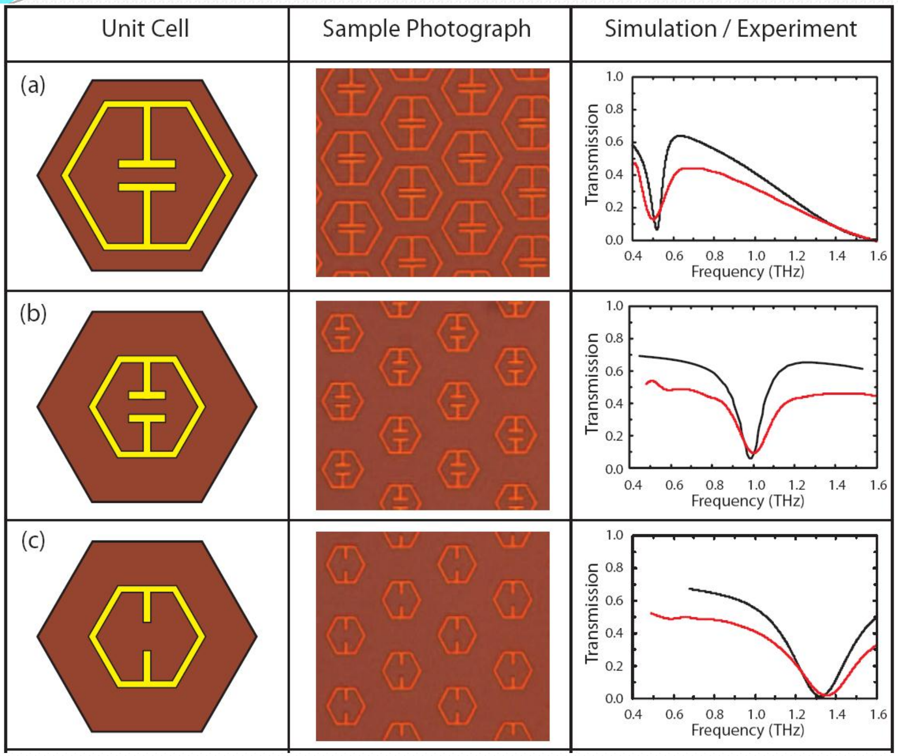
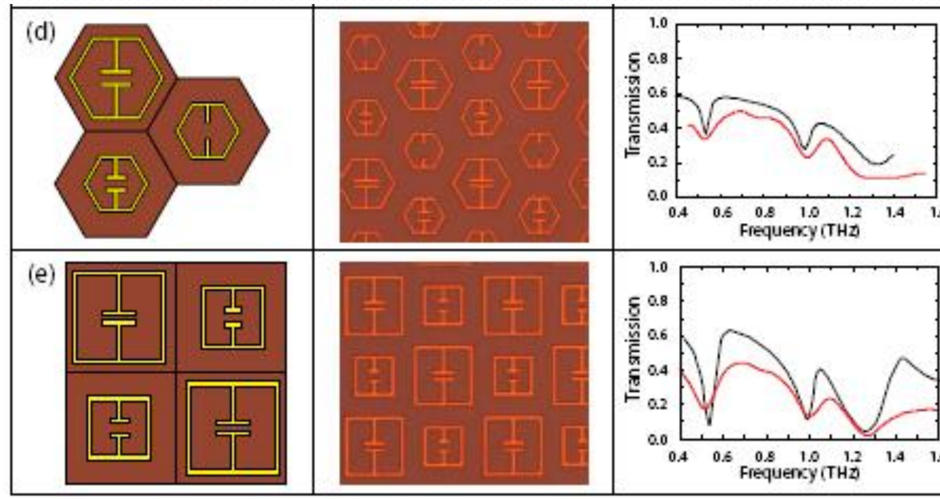
THz wallpaper metamaterials with multiple resonances



Metamaterial Persian carpets
Vol. 456, 6 November 2008, Nature



- We present novel metamaterial structures based upon various planar wallpaper groups, in both hexagonal and square unit cells.
- Our results verify that multiple element metamaterials can be successfully designed, fabricated, and measured at terahertz frequencies.

Optics Express, 16 (23), 2008

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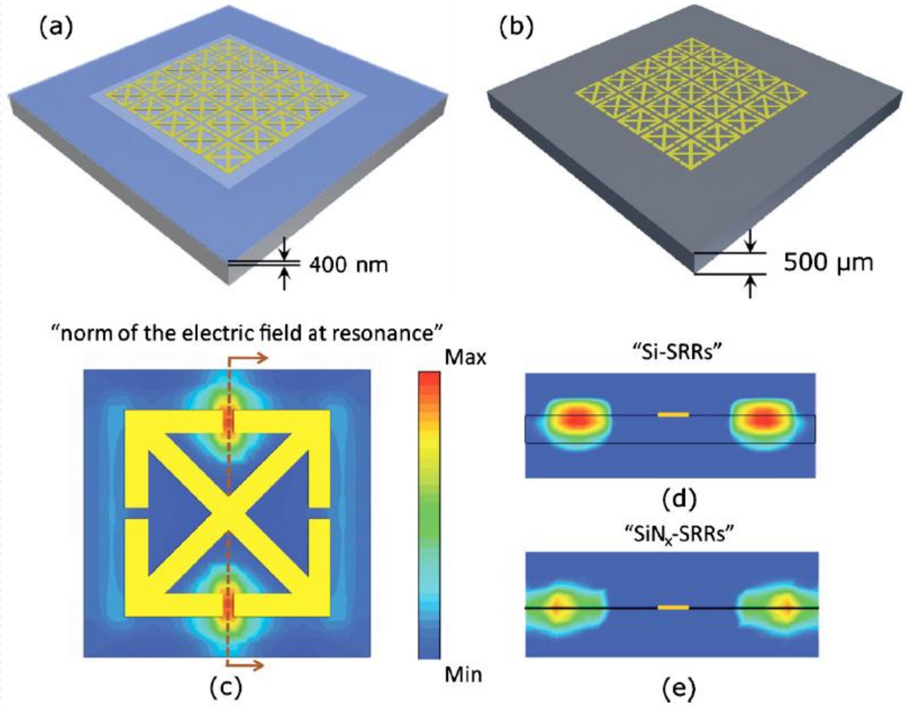
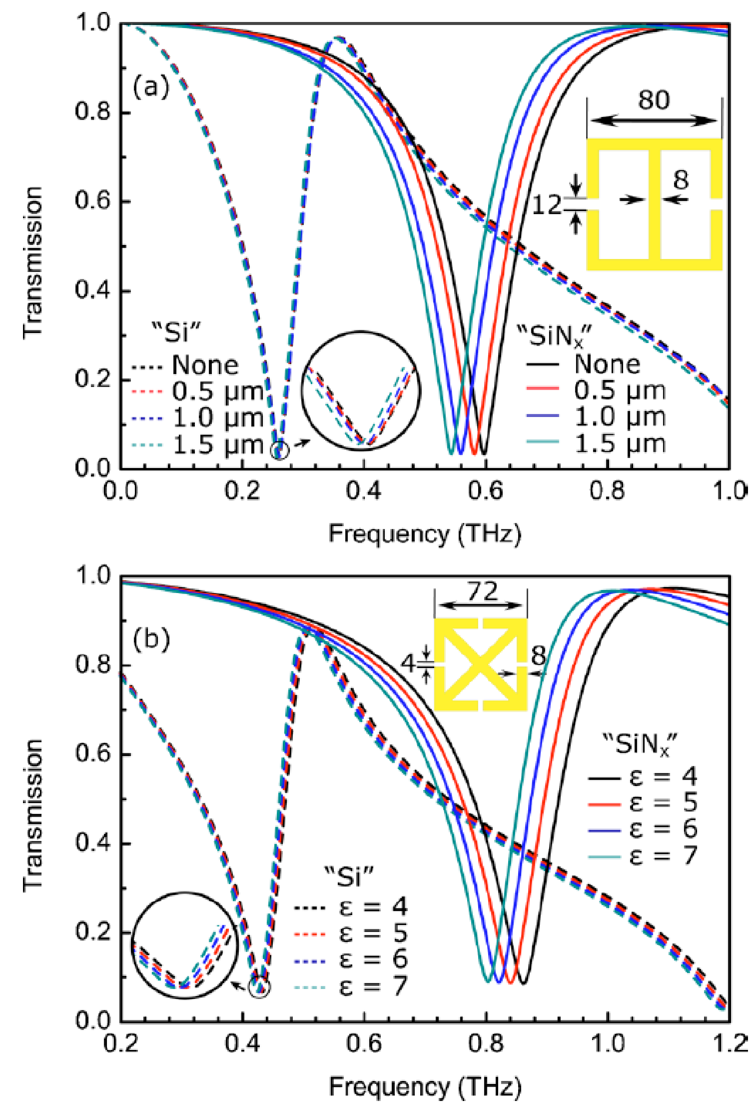
Metamaterials on Ultrathin Silicon Nitride Substrates

- Most of devices are fabricated on high-permittivity substrate such as GaAs or high resistance silicon, which contributes a large capacitance to the resonator, diminishing the changes in capacitance induced by the targets.



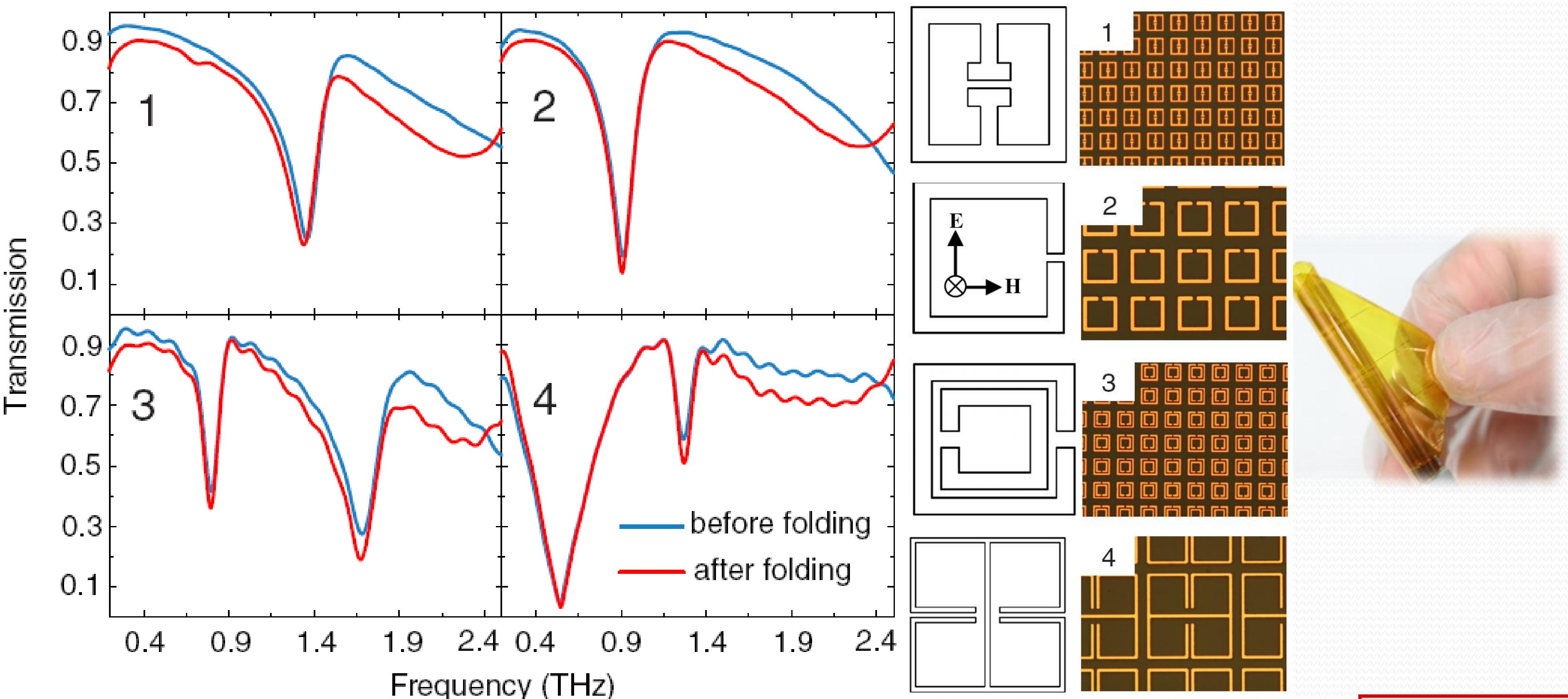


- SRR-metamaterials fabricated on thin film substrates show significantly better performance than identical SRR-metamaterials fabricated on bulk silicon substrates paving the way for improved biological and chemical sensing applications.

Applied Physics Letters, 97 (26), 2010

Flexible Metamaterials at THz Frequencies

- Fabricating resonant THz metamaterials on free-standing polyimide substrates, which are highly mechanically flexible and transparent to THz radiation. The low-loss polyimide substrates can be as thin as 5.5 μm yielding robust large-area metamaterials which are easily wrapped into cylinders with a radius of a few millimeters. These results pave the way for creating multilayered non-planar electromagnetic composites.



Journal of Physics D: Applied Physics, 41 (23), 2008

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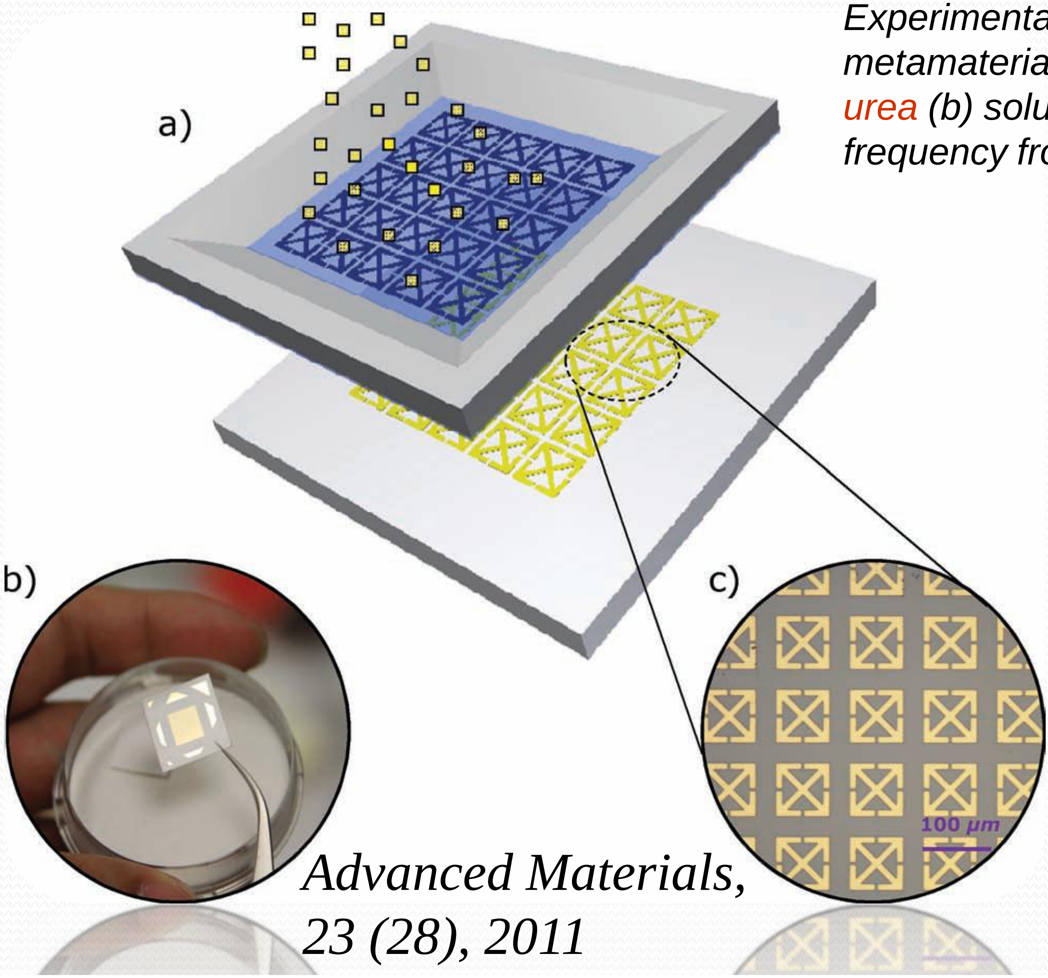
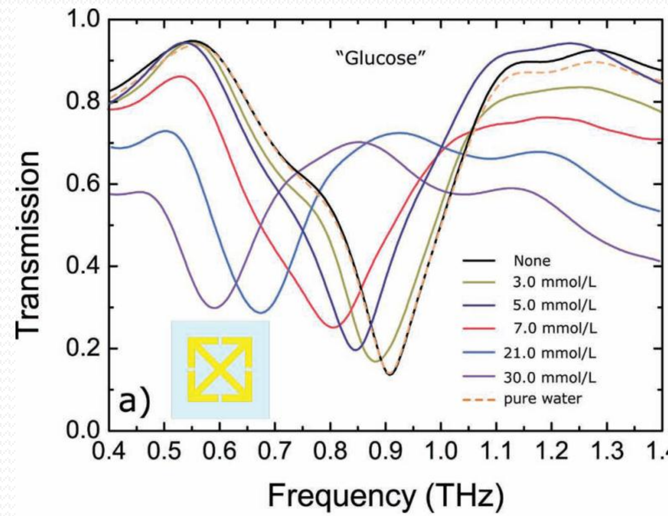
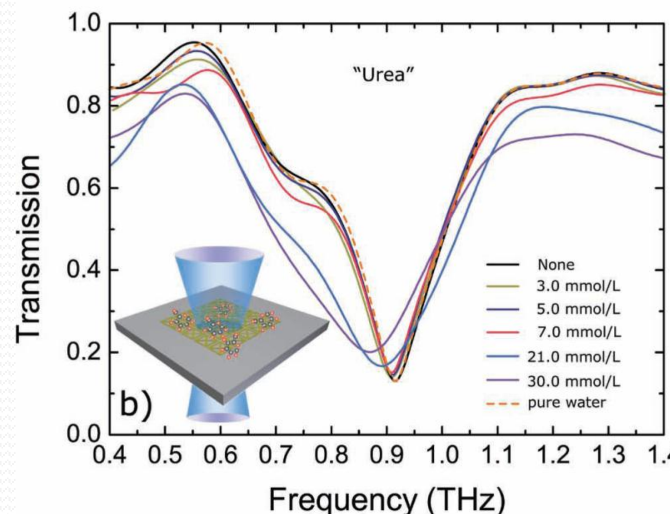
Metamaterials on Paper as a Sensing Platform

Experimentally measured transmission spectra of the paper metamaterial samples coated with a series of glucose (a) and urea (b) solutions with varying concentrations as function of frequency from 0.4 THz to 1.4 THz.



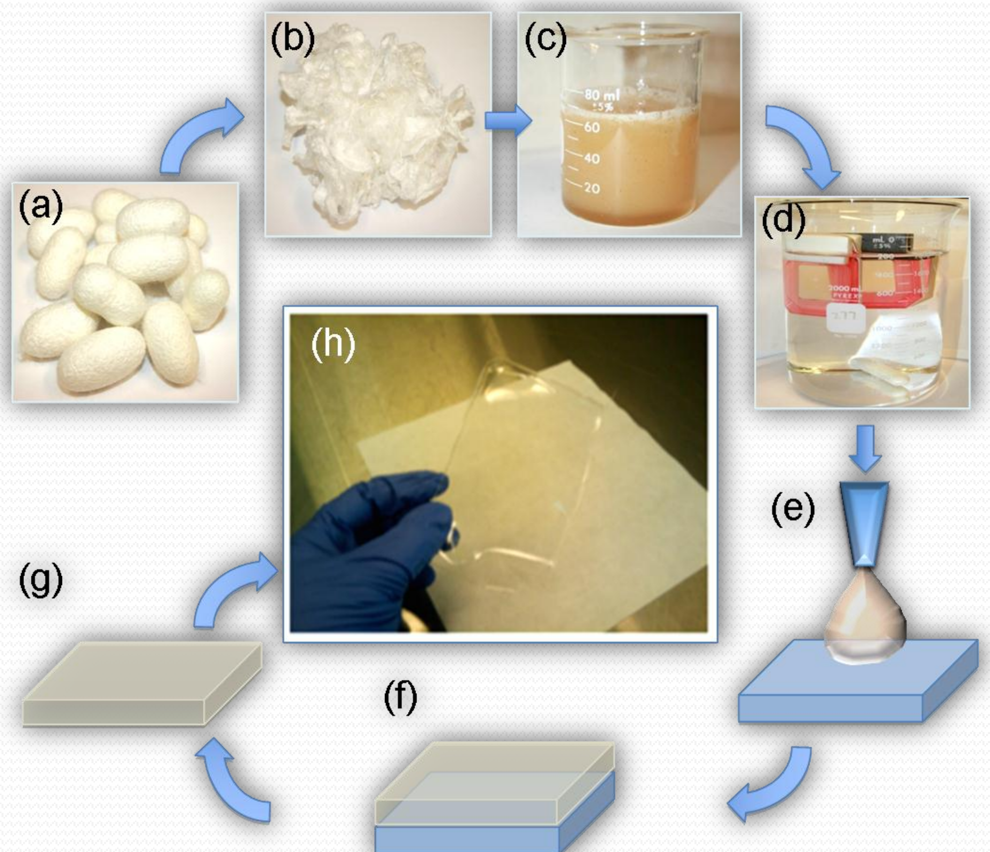
Advanced Materials, 23 (28), 2011

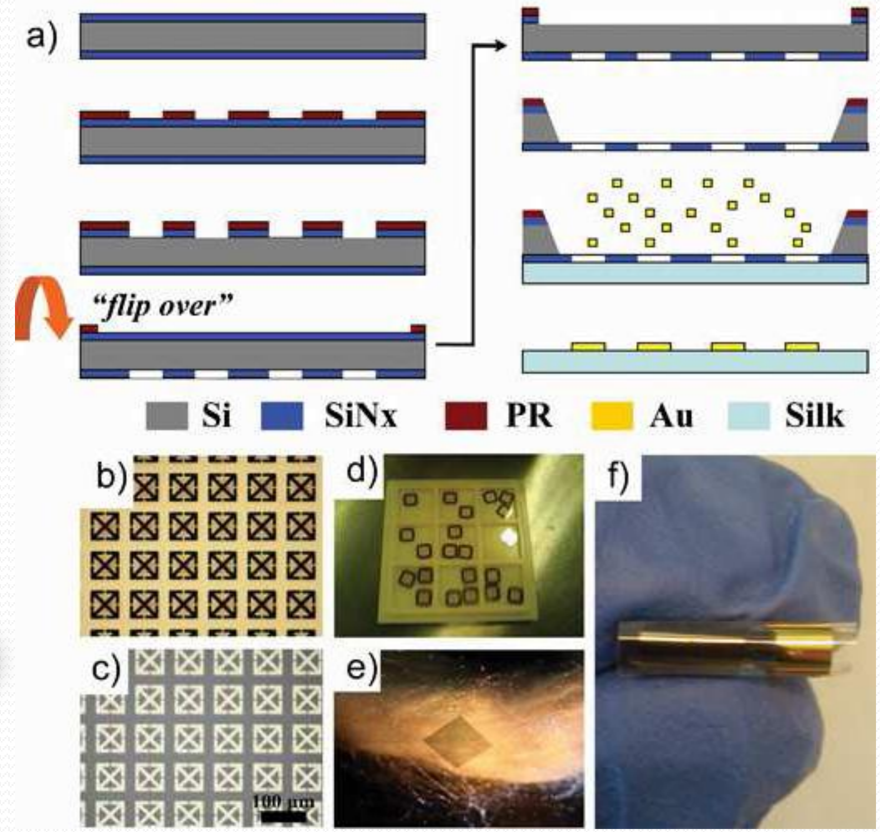




There is increasing interest in the development of cost-effective, practical, portable, and disposable diagnostic devices suited to on-site detection and analysis applications, which hold great promise for global health care, environmental monitoring, water and food safety, as well as medical and threat reductions.

Silk Metamaterials at THz Frequencies

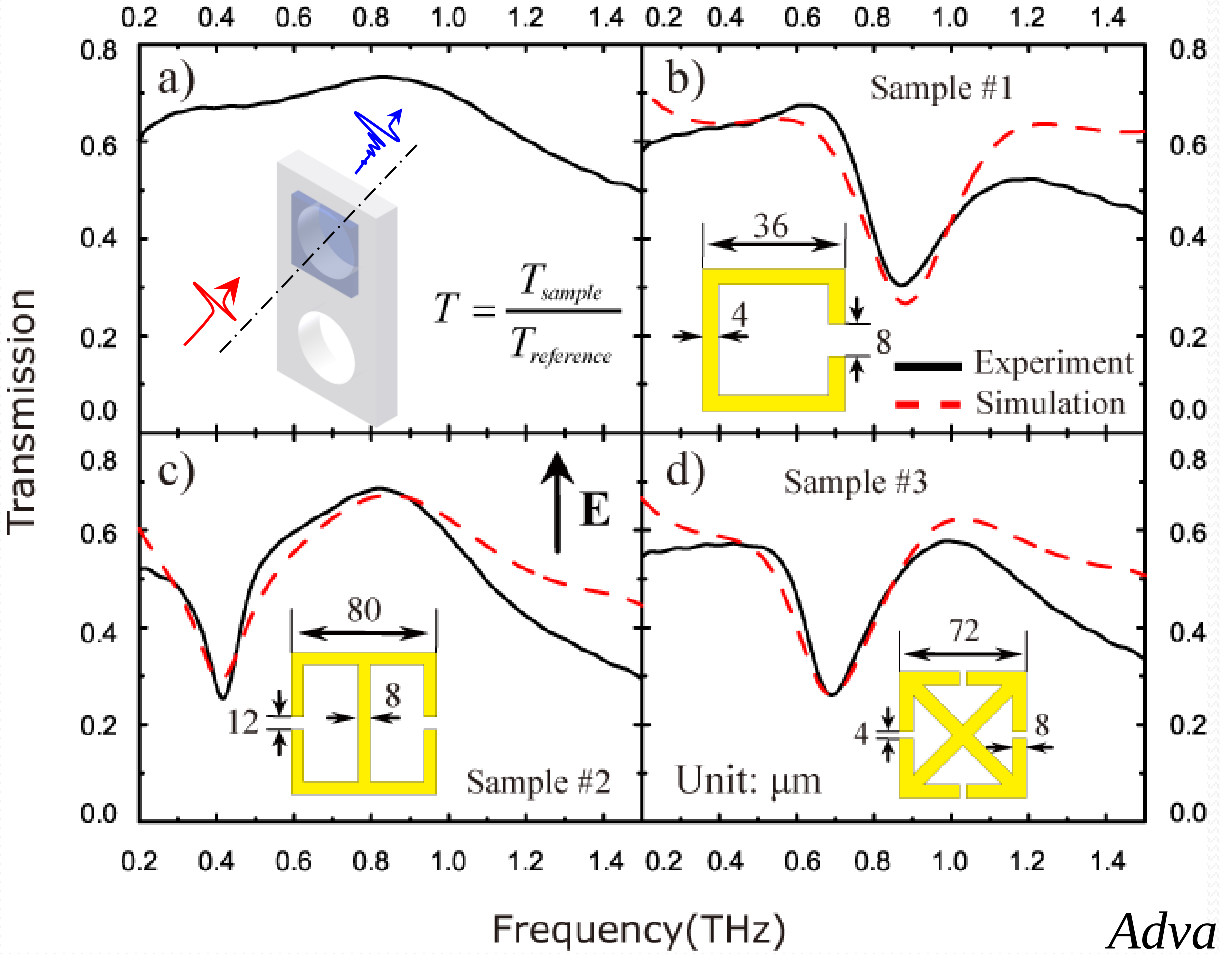


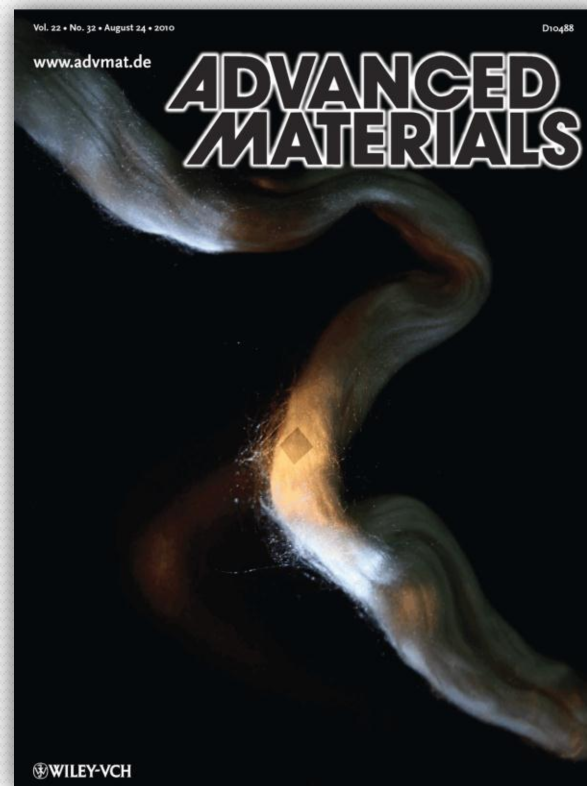


- The metamaterial structures are sprayed directly on the pre-made silk films with microfabricated stencils using a shadow mask evaporation technique.
- The entire fabrication process is conducted in a dry, chemical-free environment preventing any possible contamination, helping to maintain the integrity and biocompatibility of the silk films.

Advanced Materials, 22 (32) 2010

Silk Metamaterials at THz Frequencies





Advanced Materials, 22 (32) 2010

- Directly spray large area metamaterial structures on biocompatible silk substrates which exhibit strong resonances at desired frequencies, opening opportunities for new bioelectric and biophotonic applications including *in vivo* bio-tracking, bio-mimicry, silk electronics, and implantable biosensors and biodetectors.

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THz Metamaterial "Perfect" Absorbers

- Materials can be regarded as an effective medium characterized by a complex electric permittivity $\varepsilon = \varepsilon_1 + i\varepsilon_2$ and complex magnetic permeability $\mu = \mu_1 + i\mu_2$.

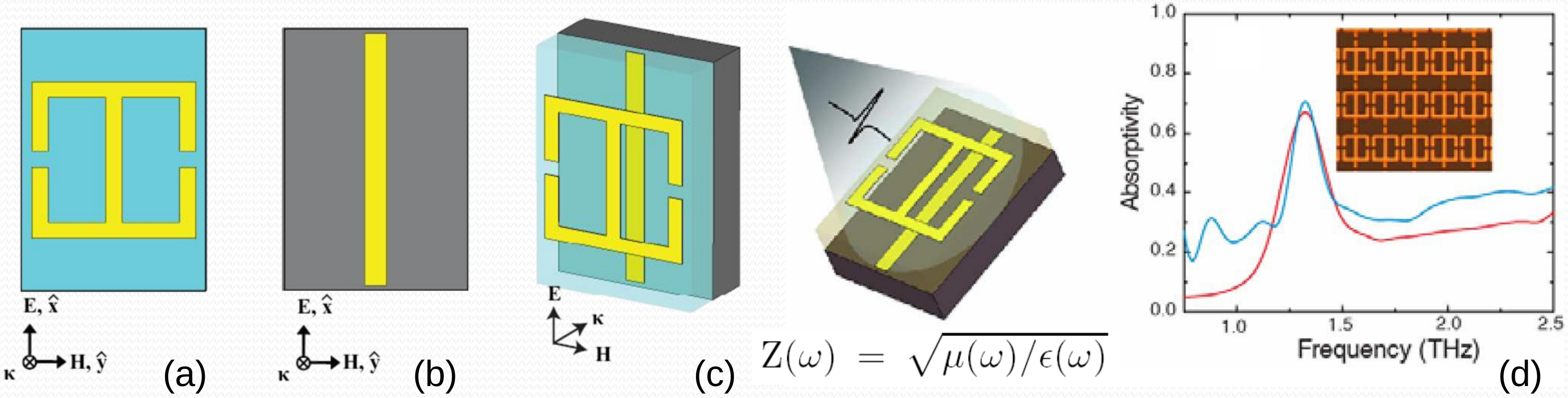
- Considerable effort has focused on the real parts of permittivity (ε_1) and permeability (μ_1) to create a negative refractive material.

  To create such structures, it is important to minimize losses (over the operating frequency range) associated with the imaginary portions (ε_2 and μ_2) of the effective response functions.

- Conversely, for many applications, it would be desirable to maximize the loss, which is an aspect of metamaterials research that, to date, has received less attention.

  Such an absorber would be of particular importance at terahertz frequencies, where it is difficult to find naturally occurring materials with strong absorption coefficients that, further, would be compatible with standard microfabrication techniques.

THz Metamaterial "Perfect" Absorbers



$$Z(\omega) = \sqrt{\mu(\omega)/\epsilon(\omega)}$$

(a) Electric resonator on the top of a polyimide spacer; (b) Cut wire on GaAs wafer; (c) Single unit cell showing the direction of propagation of incident EM wave. (d) The experimental absorptivity (in blue) reaches a maximum value of 70% at 1.3 THz.

- Goal: The electromagnetic response of metamaterials can be *tailored* by manipulating the geometries of electric and magnetic resonators *individually* to create a highly selective absorber over a narrow band at terahertz frequencies.
- Significance: The successful demonstration of the high absorber will hold great promise for future applications which includes metamaterial-based structures for creating a narrow-band, low thermal mass absorber as required for thermal sensing applications.

Filling the THz Gap, Vol. 329, 6 June 2008, Science

Near-perfect 'black', Vol. 453, 12 June 2008, Nature

Optics Express, 16 (10), 2008

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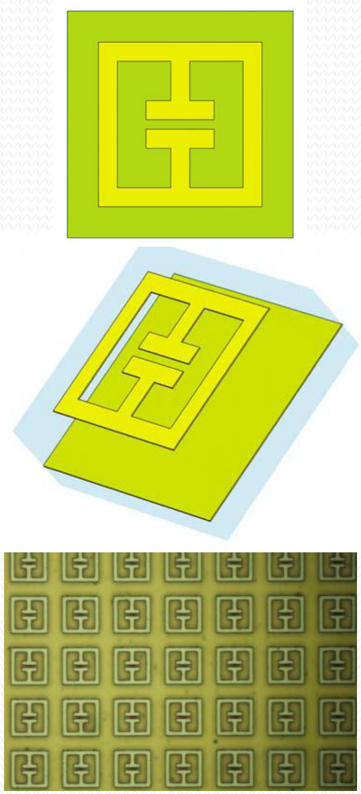
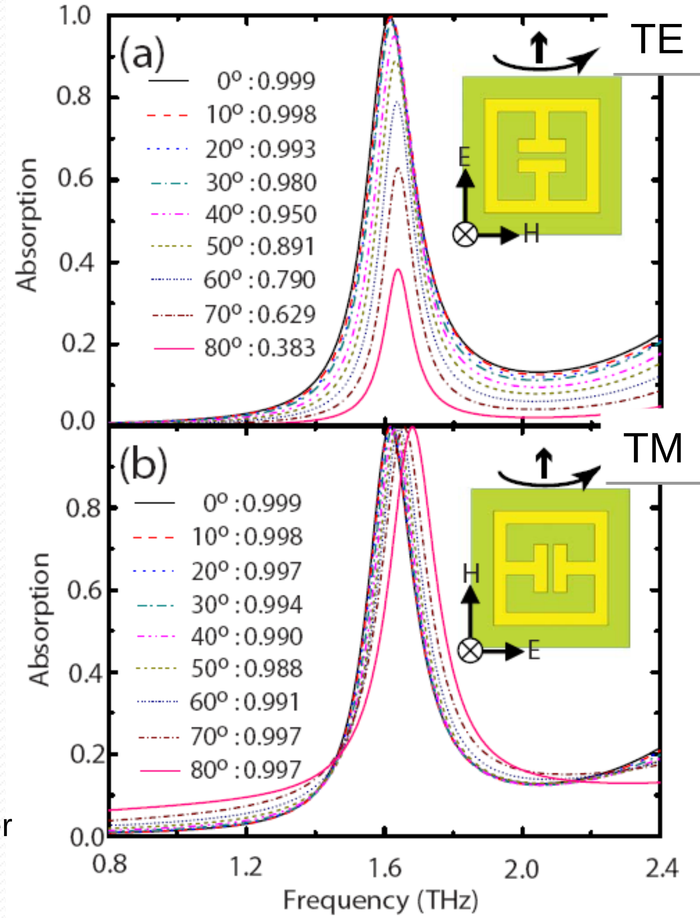
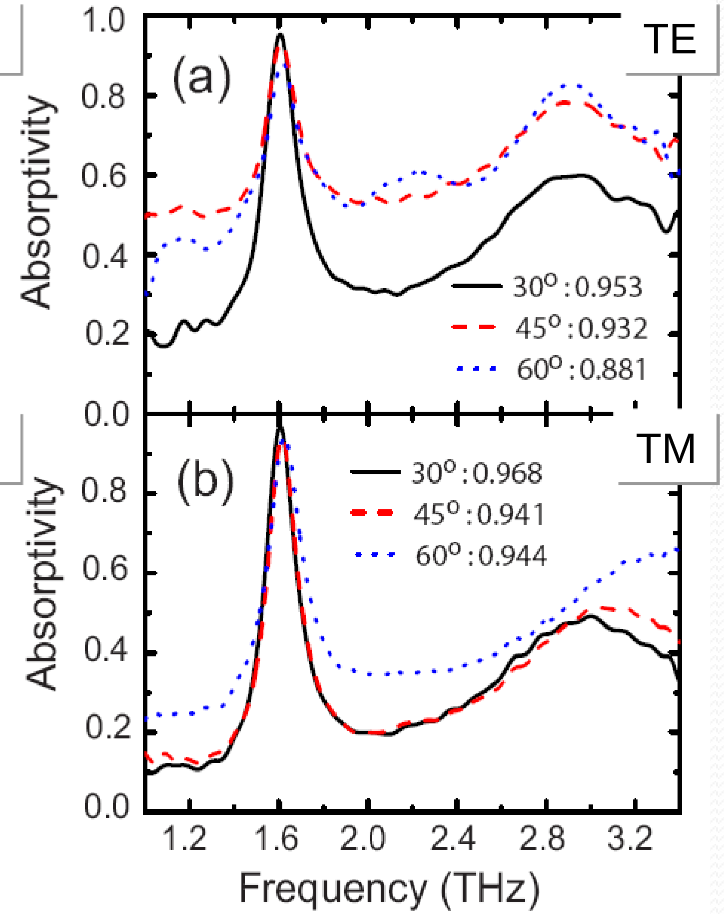
Flexible THz Wide Angle "Perfect" Absorbers



Terahertz metamaterial absorber consisting of two metallic layers and two dielectric layers.

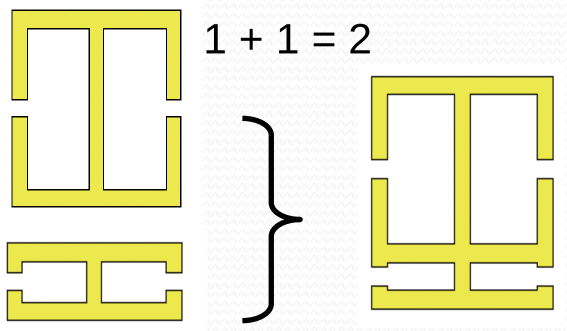




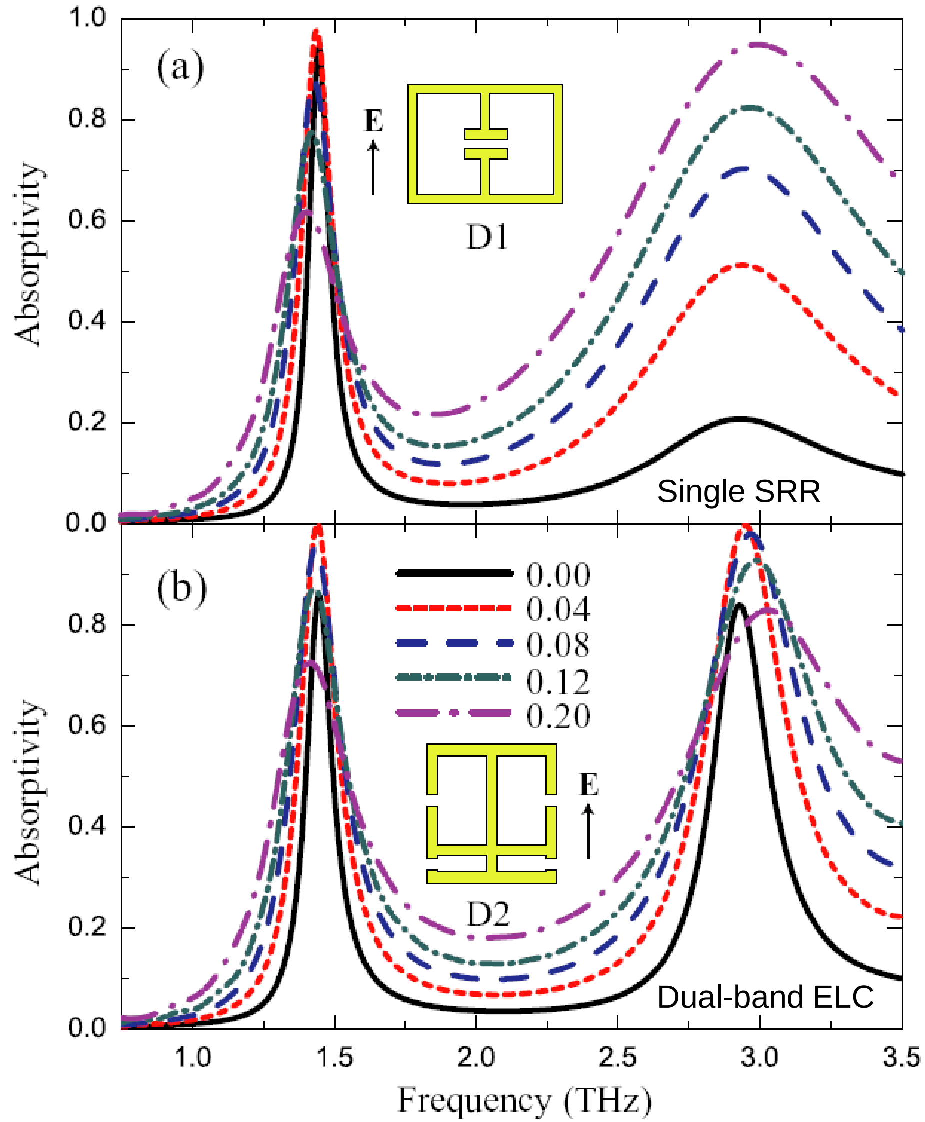
- We present the design, fabrication, and characterization of a metamaterial absorber which is resonant at terahertz frequencies. We experimentally demonstrate an absorptivity of 0.97 at 1.6 THz.
- Importantly, our absorber is only 16 μm thick, resulting in a highly flexible material that, further, operates over a wide range of angles of incidence for both transverse electric (TE) and transverse magnetic (TM) radiation.

Physical Review B, 78 (24), 2008

Dual Band Terahertz Absorbers



- Dual band terahertz metamaterial absorber consisting of a dual band electric-field-coupled (ELC) resonator and a metallic ground plane, separated by an 8 μm thick dielectric layer.
- Remarkably, the two resonance responses can be tuned and optimized *independently* at desired frequencies with comparably high absorptivity as with single band metamaterial absorbers.
- This feature provides more flexibility in multi-band absorber designs and can be readily extended to infrared and visible frequency ranges.



Journal of Physics D: Applied Physics, 43 (22) 2010

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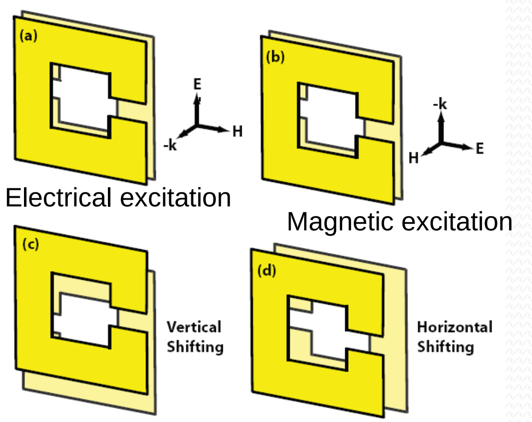
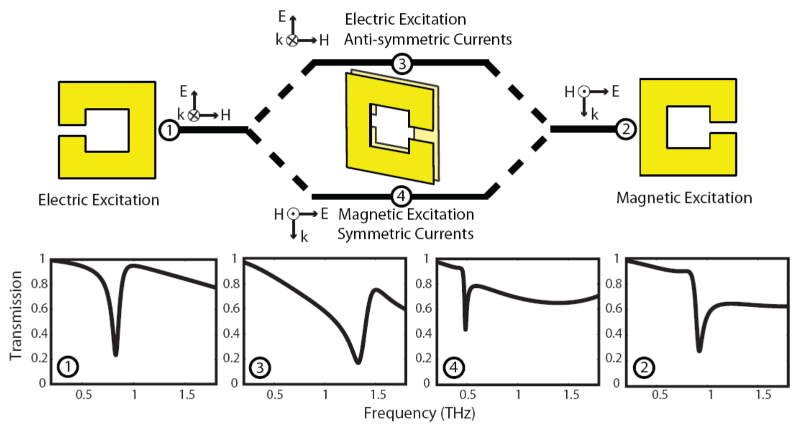
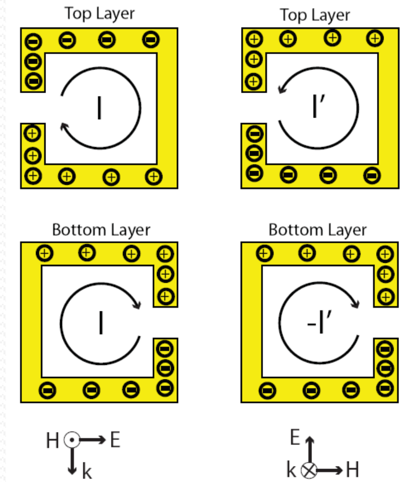
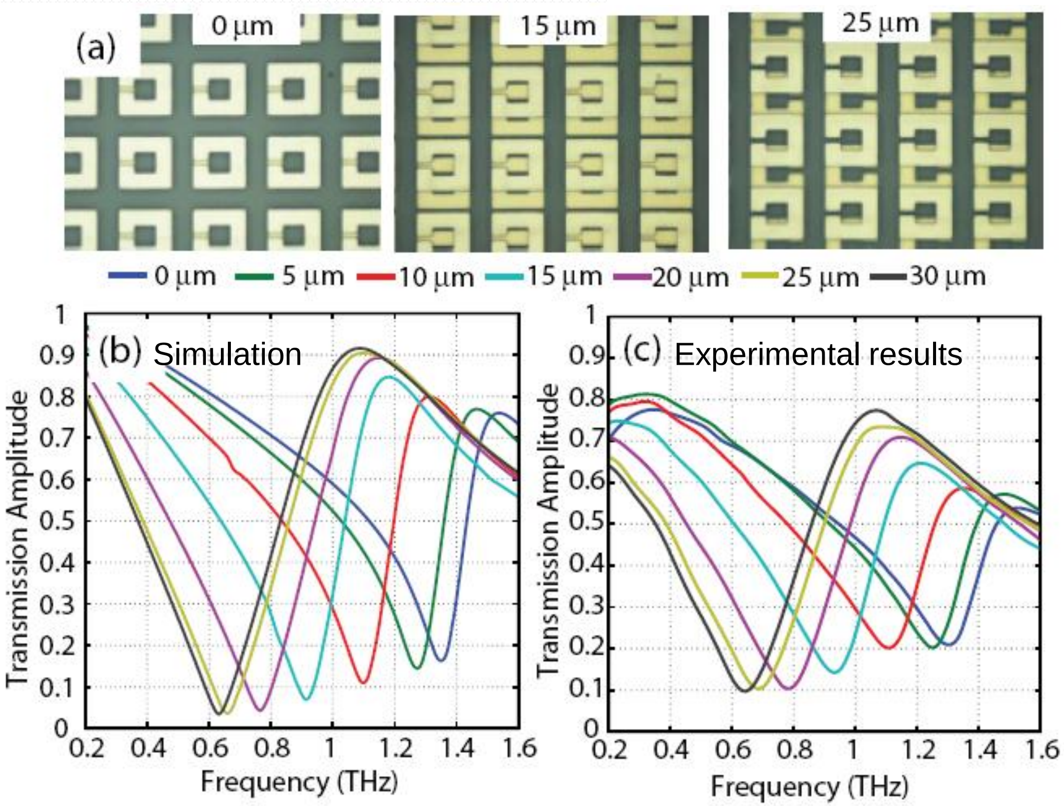
Frequency Tunable Terahertz Metamaterials







Hybridization in BC-SRRs



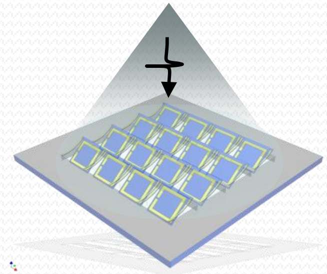
Frequency tunable MM designs at THz frequencies using broadside coupled split-ring resonator (BC-SRR) arrays:

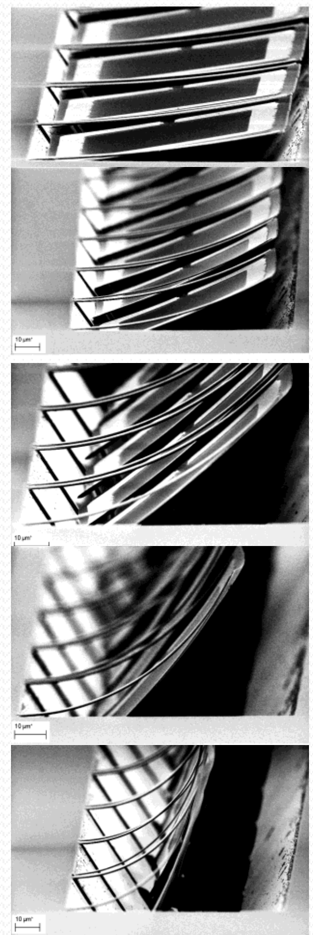
- Frequency tuning, arising from changes in near-field coupling, is obtained by in-plane displacement of the two SRR layers.
- For electrical excitation, the resonance frequency continuously redshifts as a function of displacement.
- The maximum frequency shift occurs for vertical displacement of half a unit cell, resulting in a shift of 663 GHz (51% f_0).

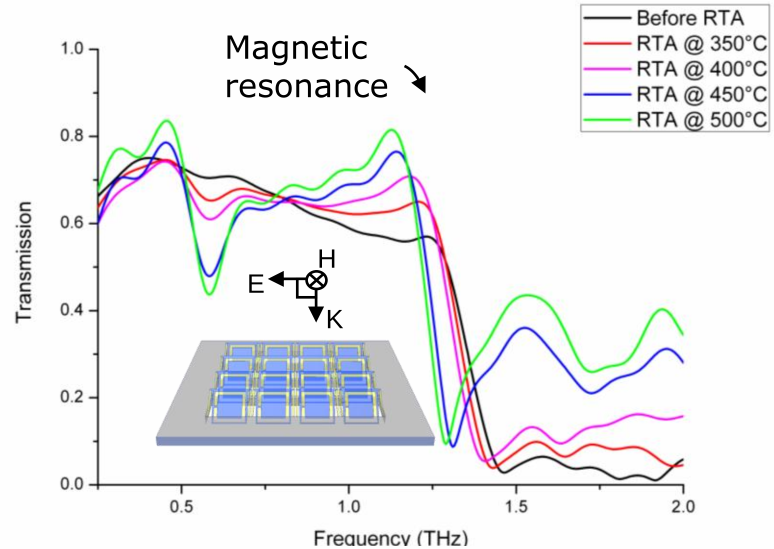
Physical Review B, 83 (19), 2011

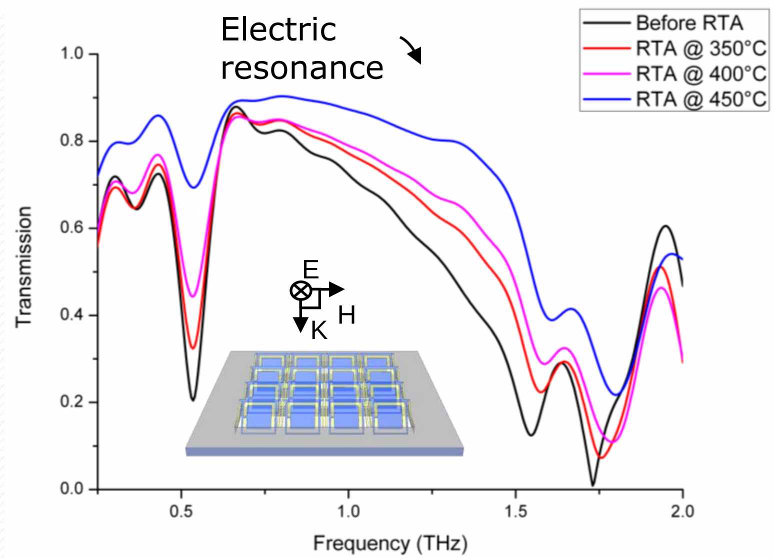
Structurally Tunable THz Metamaterials

- We demonstrate reconfigurable anisotropic metamaterials at terahertz frequencies where artificial "atoms" reorient within unit cells in response to an external stimulus.
- This is accomplished by fabricating planar arrays of split ring resonators on bimaterial cantilevers designed to bend out of plane in response to a thermal stimulus.
- We observe a marked tunability of the electric and magnetic response as the split ring resonators reorient within their unit cells.
- Our results demonstrate that adaptive metamaterials offer significant potential to realize novel electromagnetic functionality ranging from thermal detection to reconfigurable cloaks or absorbers.









Physical Review Letters, 103 (14), 2009

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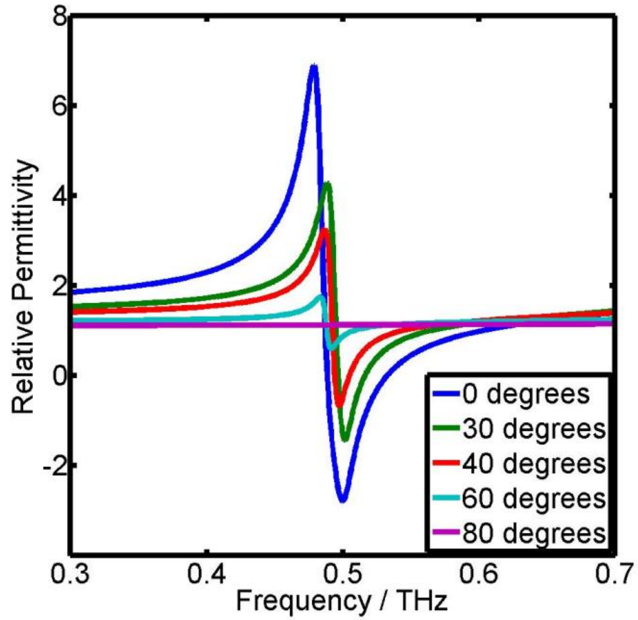
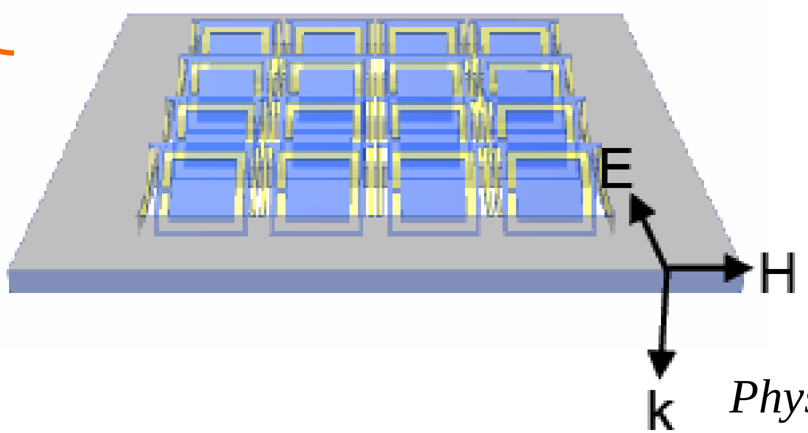
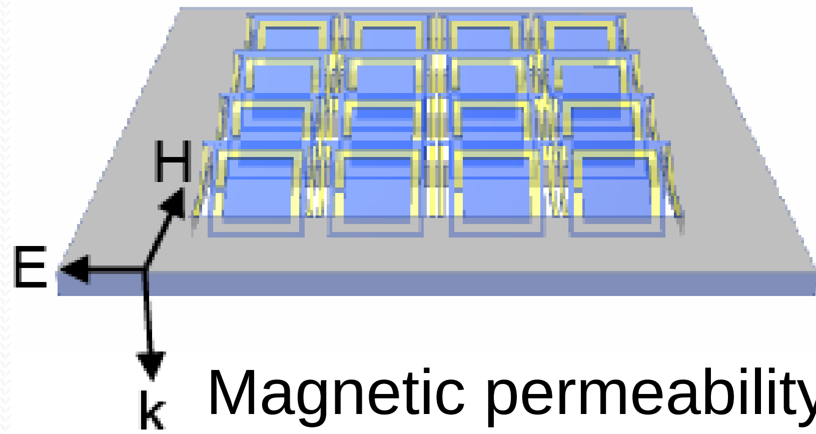
Tunable Electric and Magnetic Responses

ε

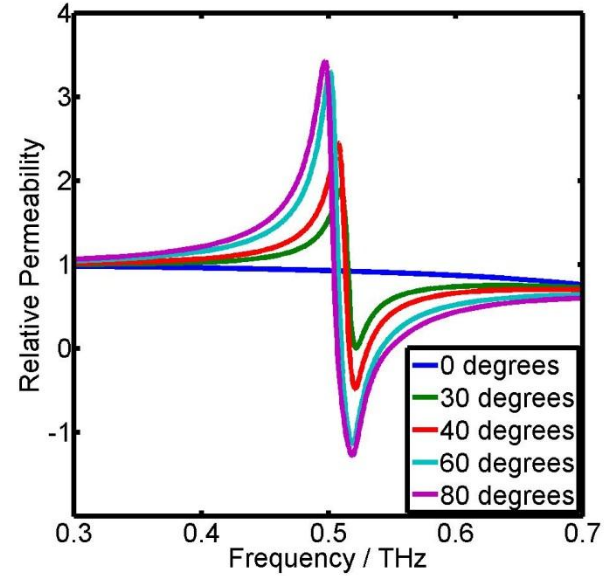


Electric permittivity





Magnetic permeability



μ

Physical Review Letters, 103 (14), 2009

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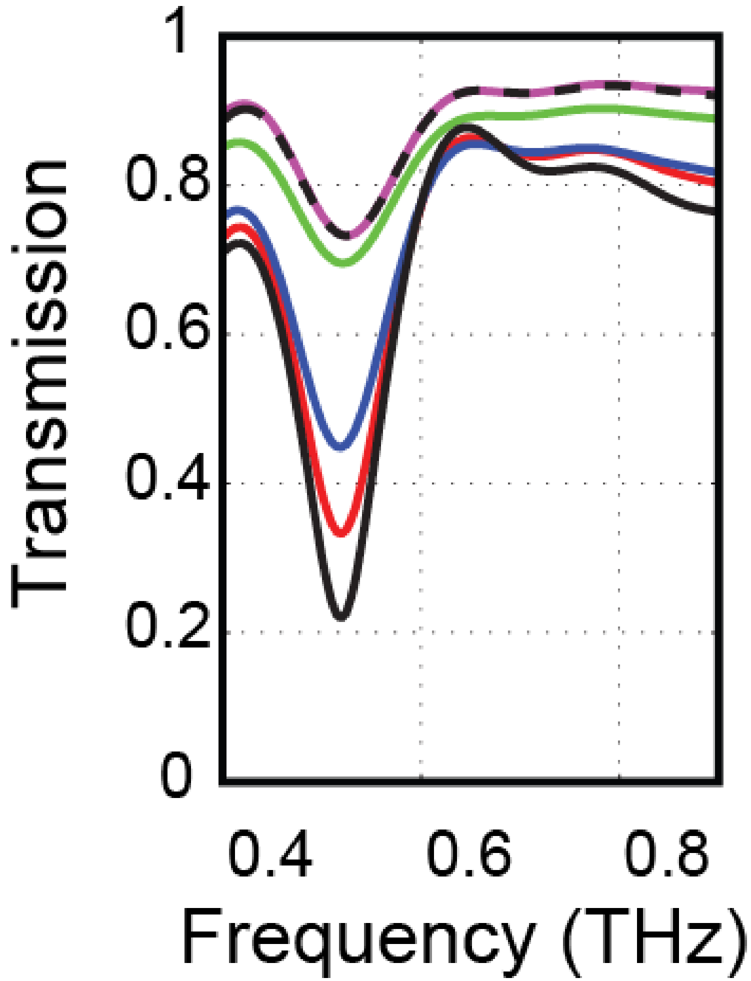
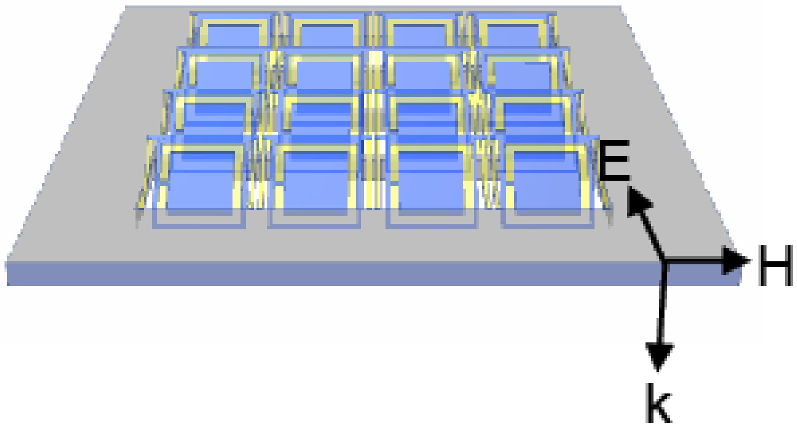
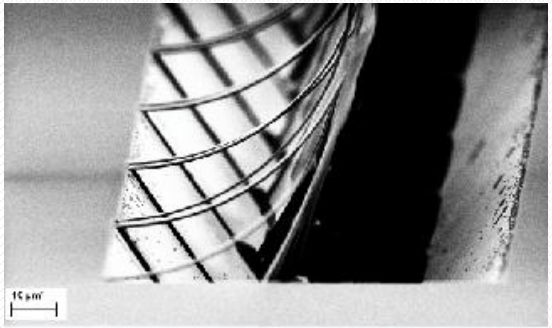
Controlling the Electric Response







Physical Review Letters, 103 (14), 2009

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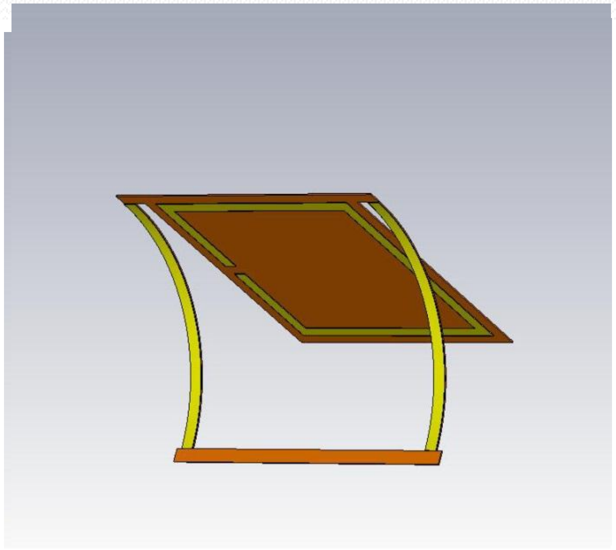
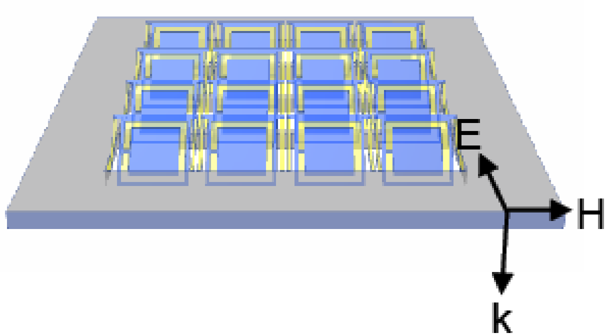
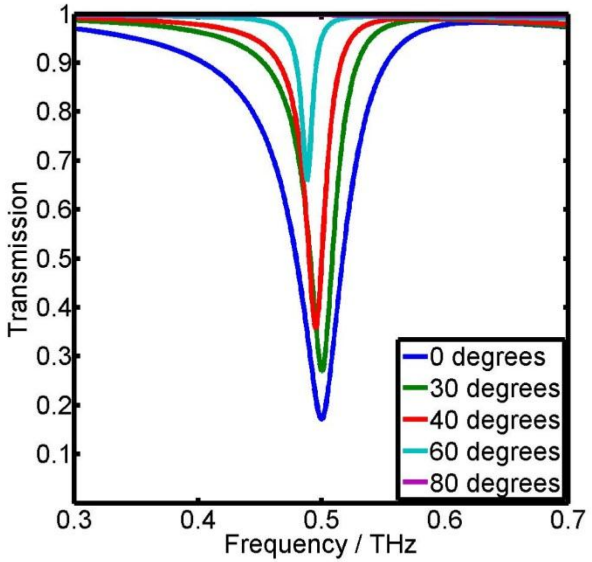
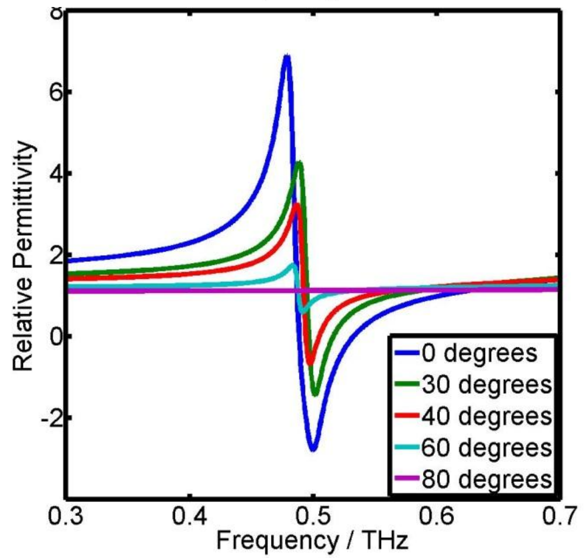
Simulations of the Electric Response









Physical Review Letters, 103 (14), 2009

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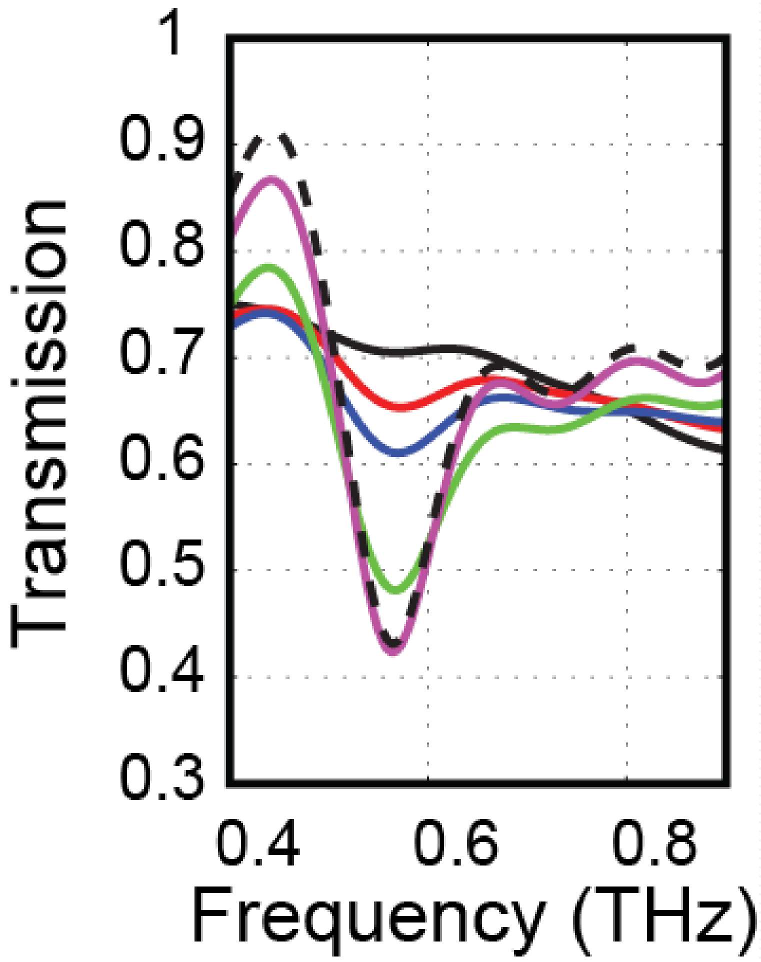
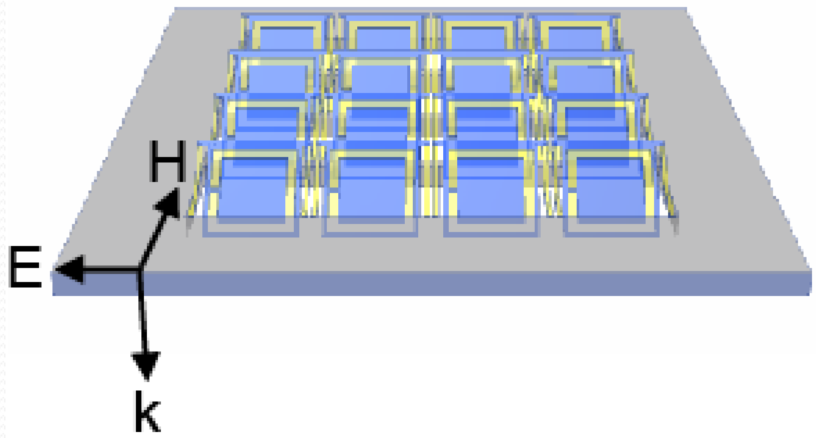
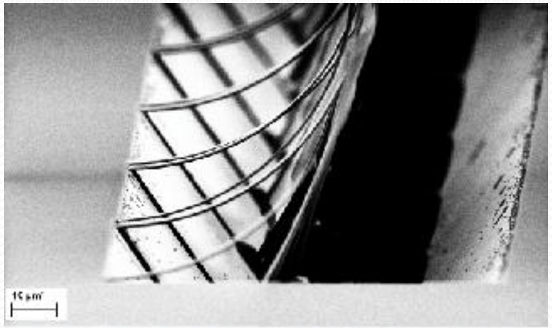
Controlling the Magnetic Response







Control of the EM response at the unit cell level

Physical Review Letters, 103 (14), 2009

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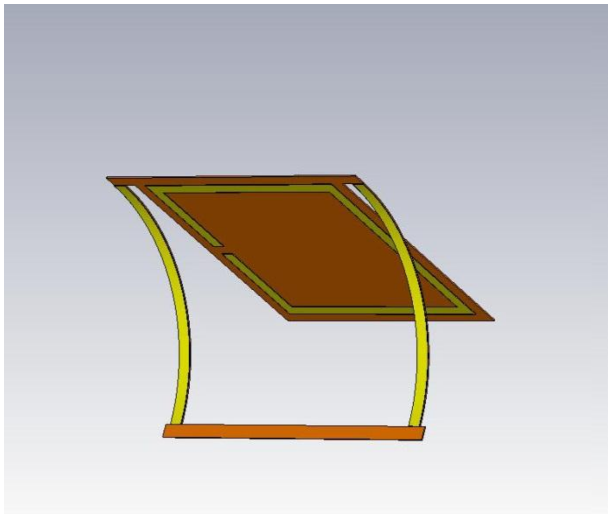
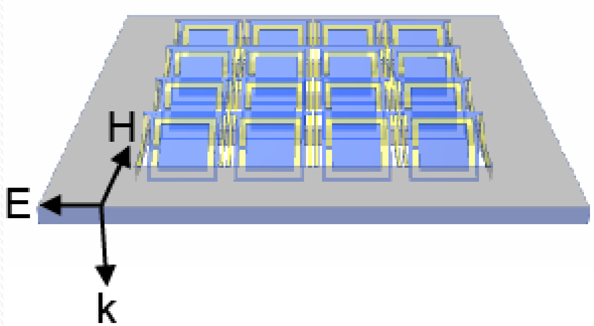
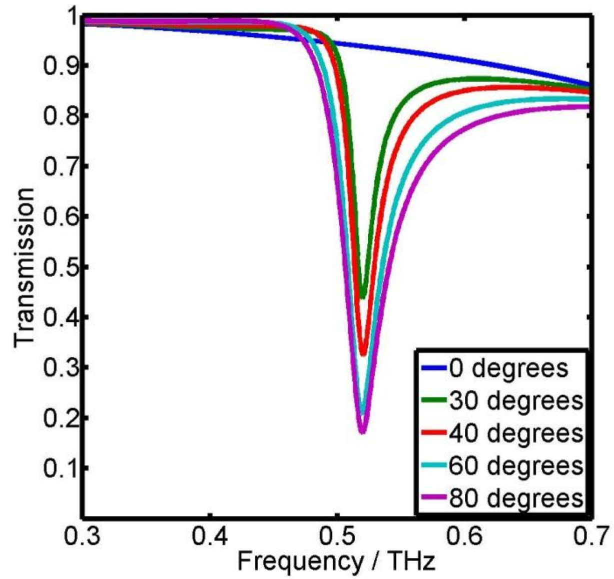
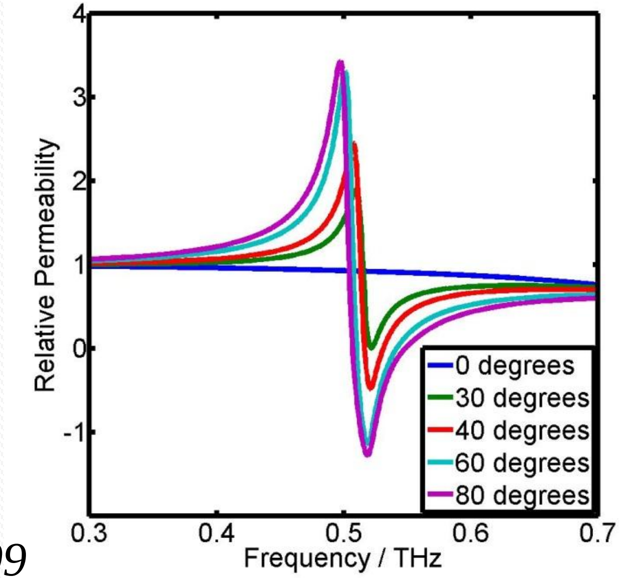
Simulations of the Magnetic Response





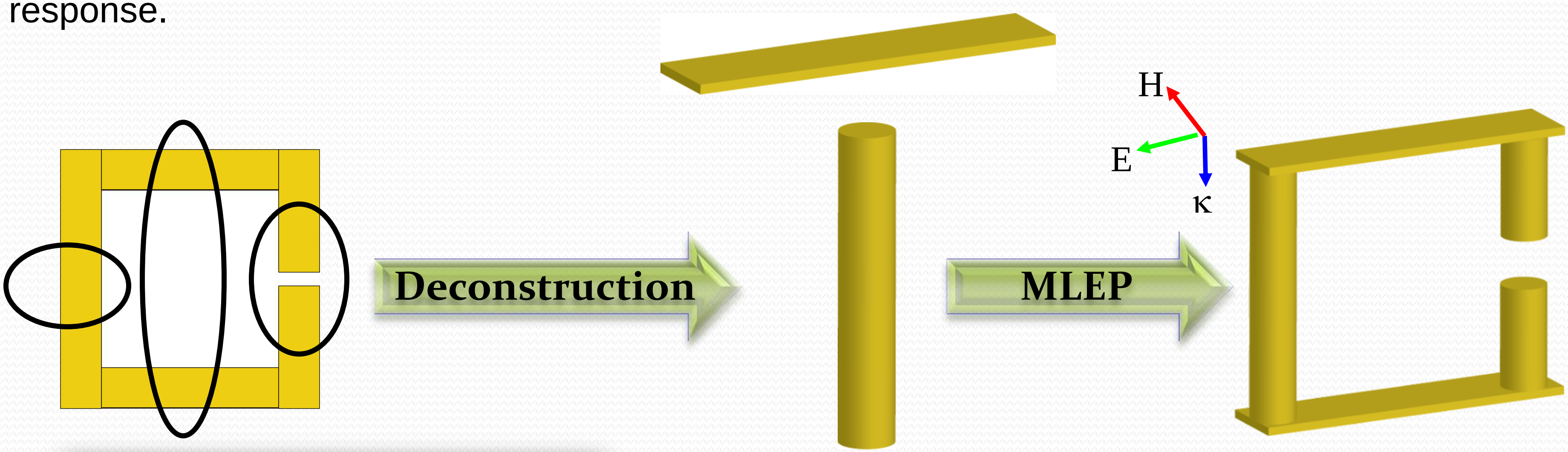


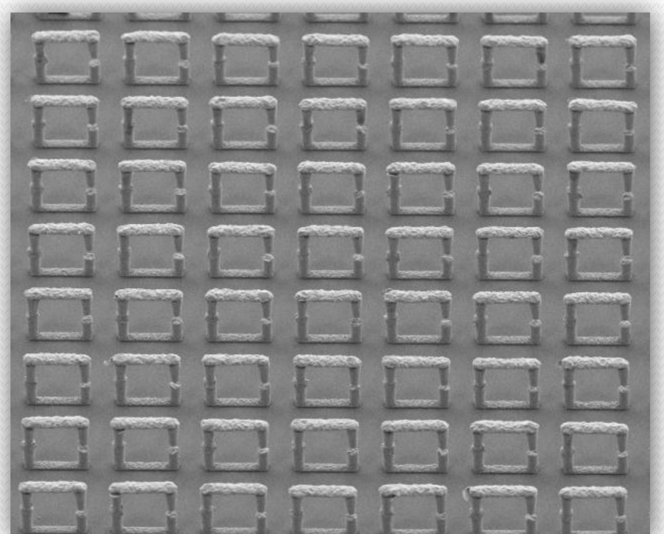


Physical Review Letters, 103 (14), 2009

Stand-up Magnetic Metamaterials at THz Frequencies

To obtain a magnetic from planar SRR structures at normal incidence requires at least two planar layers. This creates a composite effect that cannot easily be decoupled from the electric response.





Building Blocks

For planar SRRs at normal incidence, magnetic excitation does not occur. This is in contrast to out of plane SRRs, where when the incident THz radiation is polarized, the excitation is purely magnetic.

Optics Express, 19 (13), 2011

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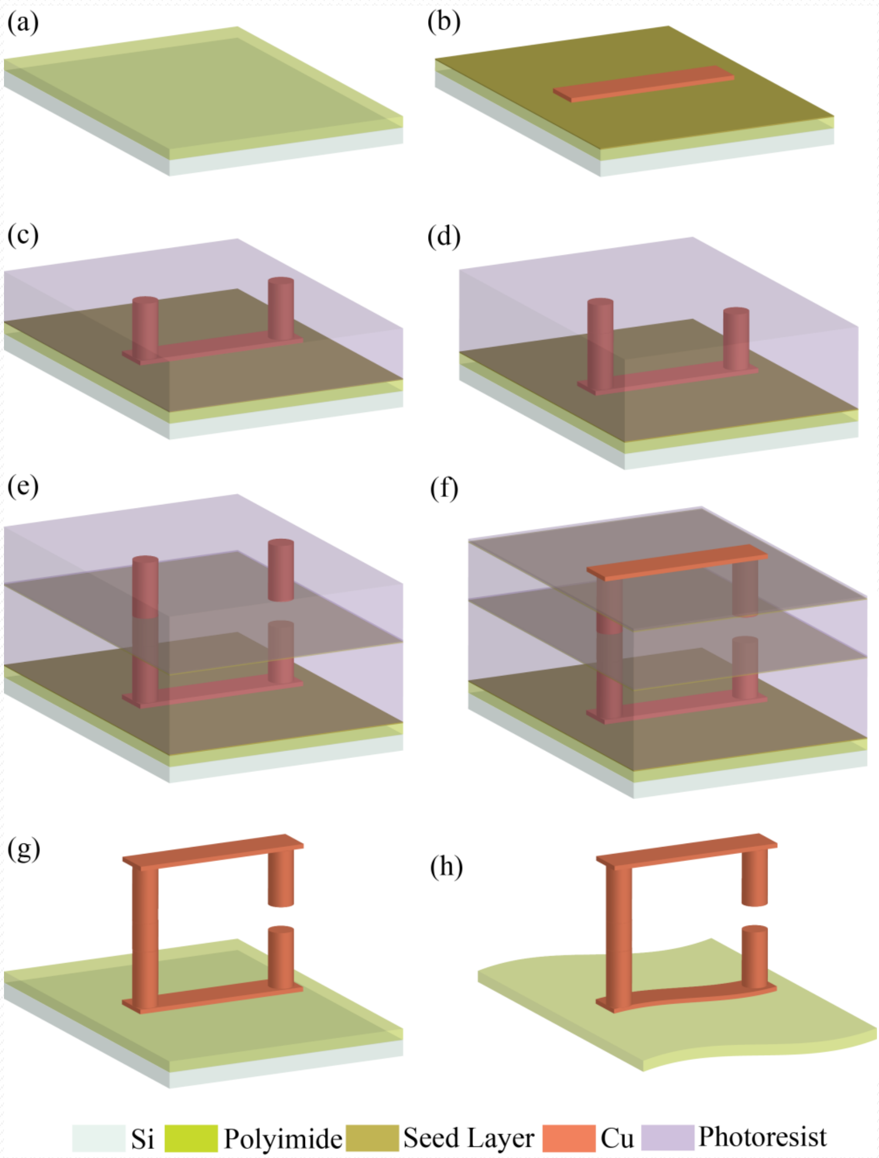
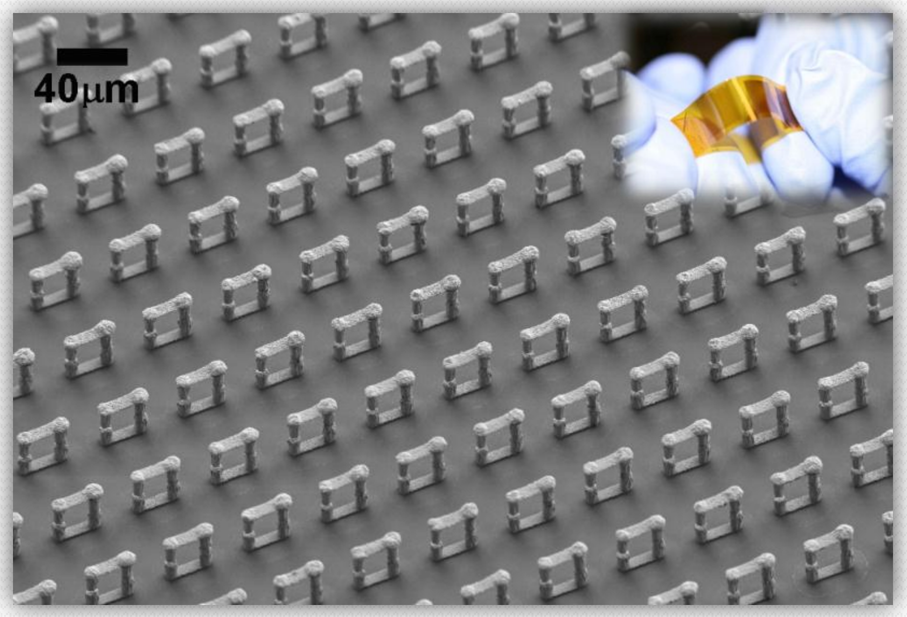
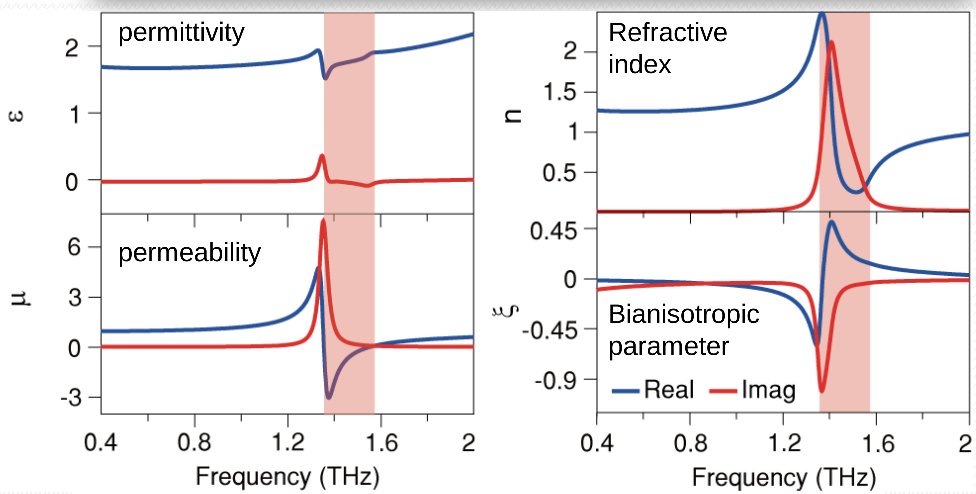
Stand-up Magnetic Metamaterials at THz Frequencies







Metamaterials standing on a 30μm polyimide substrate

Optics Express, 19 (13), 2011

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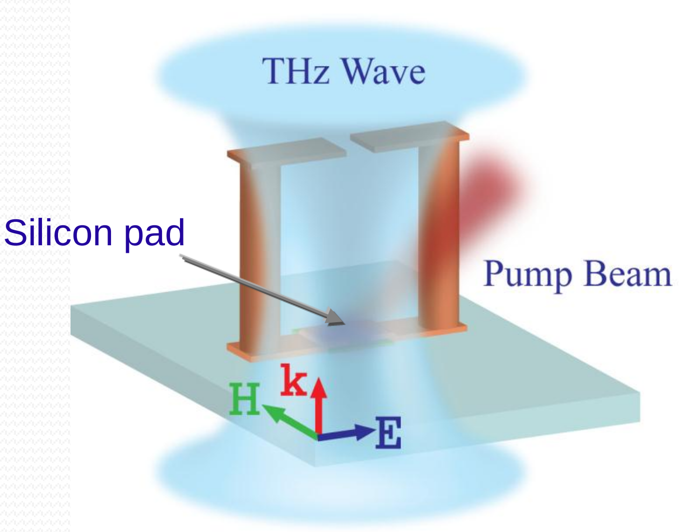
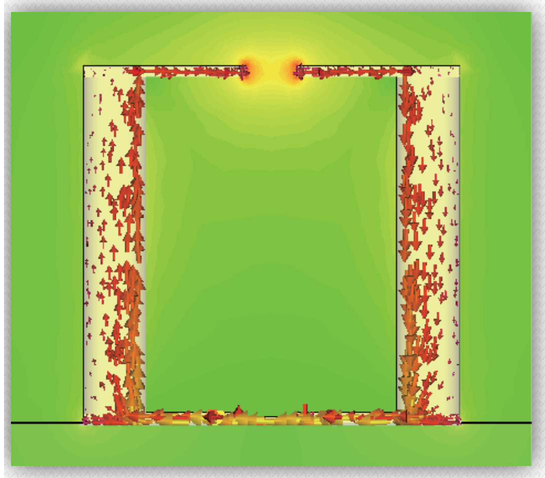
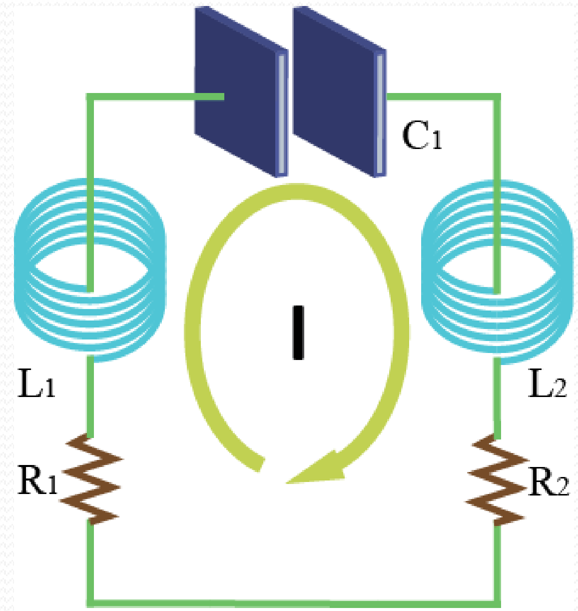
Distributed Capacitance Tuning - Design



Double splits ring resonator





Optics Express, 19 (13), 2011

- A silicon pad is patterned between the bottom gap of a double splits ring resonator.
- Without photoexcitation, in the circuit model, two capacitances are connected in series. There's a circulation current in the ring showing the LC resonance.
- Under the normal incidence of THz wave with magnetic field normal to the plane, a LC resonance is induced in this ring.
- Under a certain photoexcitation, the carriers in the silicon is excited so that the capacitance of the bottom in the LC circuit is shorted.
- Then the resonant frequency shifts to lower frequency.

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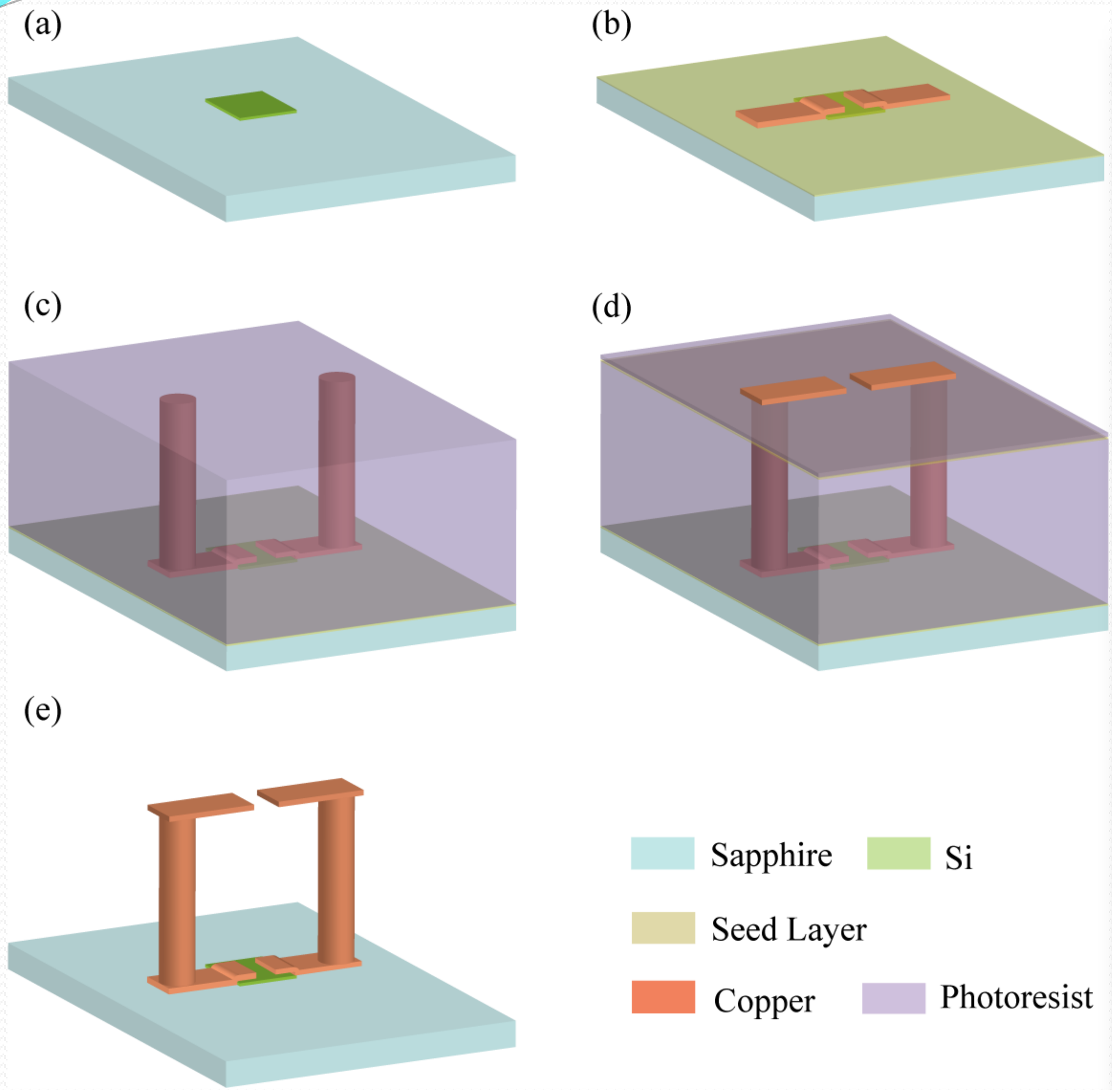
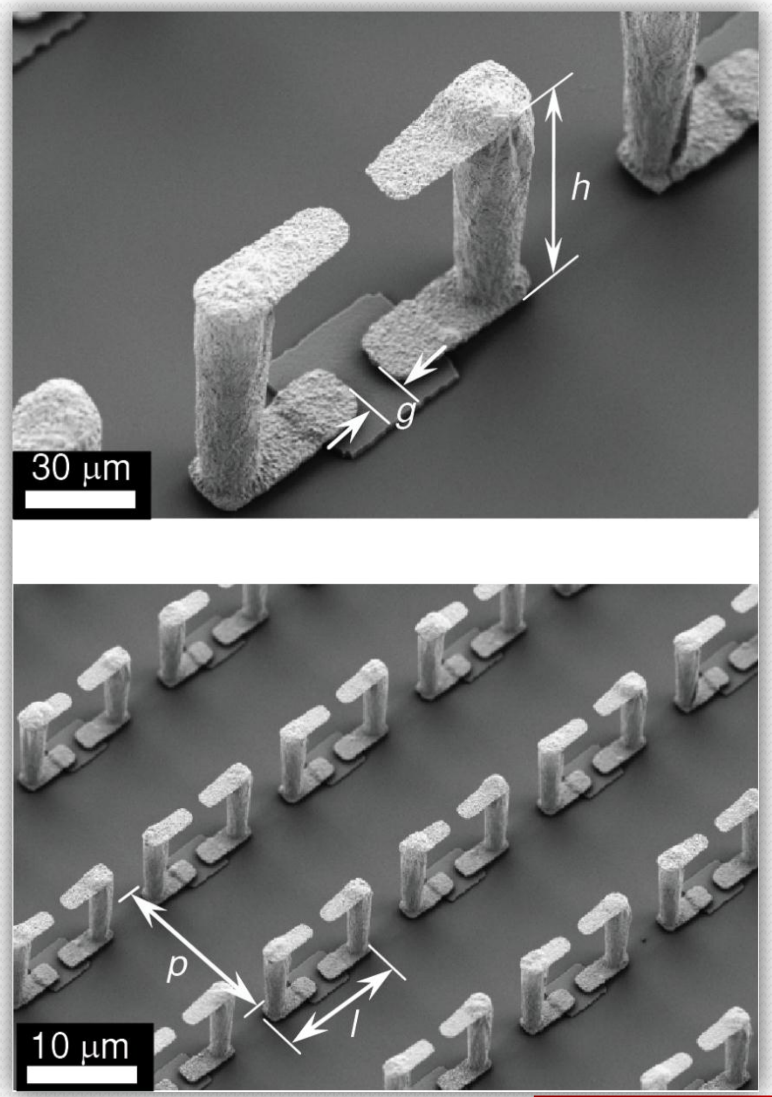
Distributed Capacitance Tuning - Fabrication





Double splits ring resonator with a silicon pad patterned between the bottom gap

Optics Express, 19 (13), 2011

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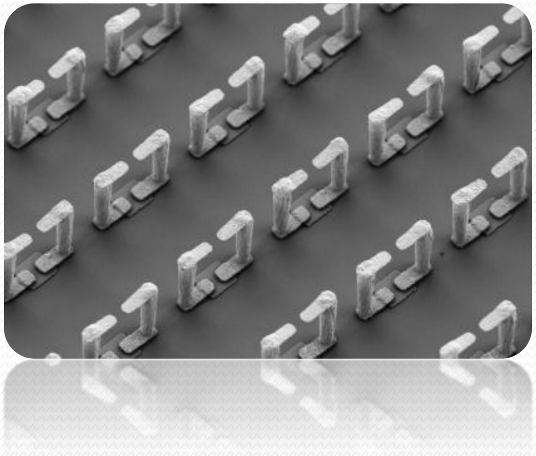
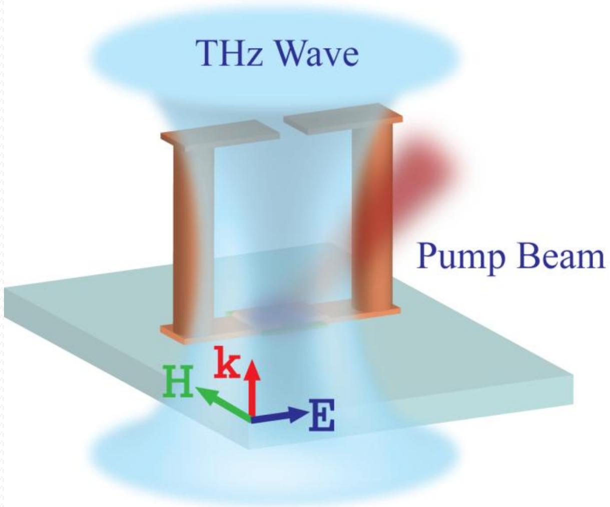
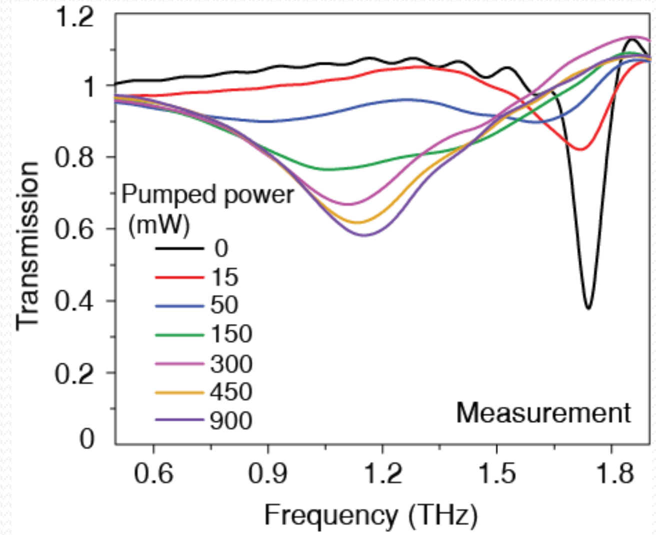
Broadband Tuning 3D Metamaterials



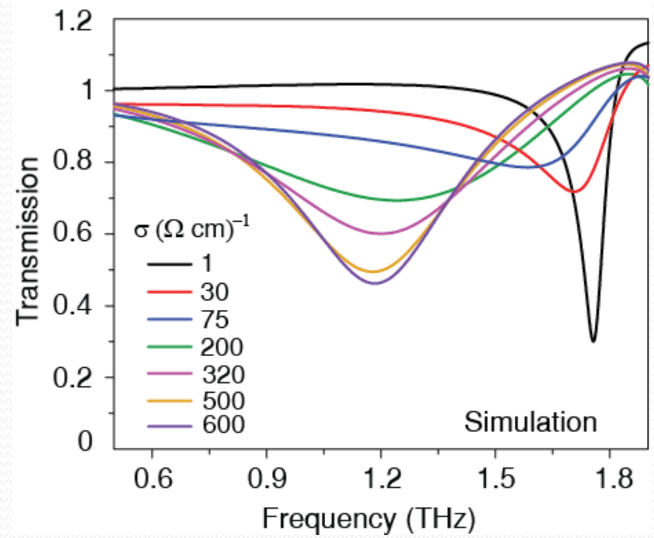




- ★ Photoexcitation of free carriers in the silicon was achieved using optical excitation with 35-fs ultrafast pulses with a center wavelength of 800 nm.

- ★ This optical pump pulse was set to arrive 10 ps before the THz probe beam ensuring a near steady-state accumulation of carriers due to their long lifetime in silicon.

- ★ Over 30% of tunability of the resonance frequency is achieved by photoexcitation of 3D metamaterials.



Optics Express, 19 (13), 2011

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MEMS and Metamaterials: A Perfect Marriage at Terahertz Frequencies

Single planar metamaterials on GaAs substrate

THz wallpaper metamaterilas with multiple resonances

Metamaterilas in ultrathin silicon nitride substrates

Flexible metamaterials at terahertz frequencies

Metamaterials on paper as a sensing platform

Silk metamaterilas at terahertz frequencies

THz metamaterial 'perfect' absorbers (flexible, wide angle, dual band)

Tunable metamaterials at terahertz frequencies (frequency, structurally)

Stand-up metamaterials at terahertz frequencies (capacitance, broadband tuning)

Microwave and terahertz wave sensing with metamaterials

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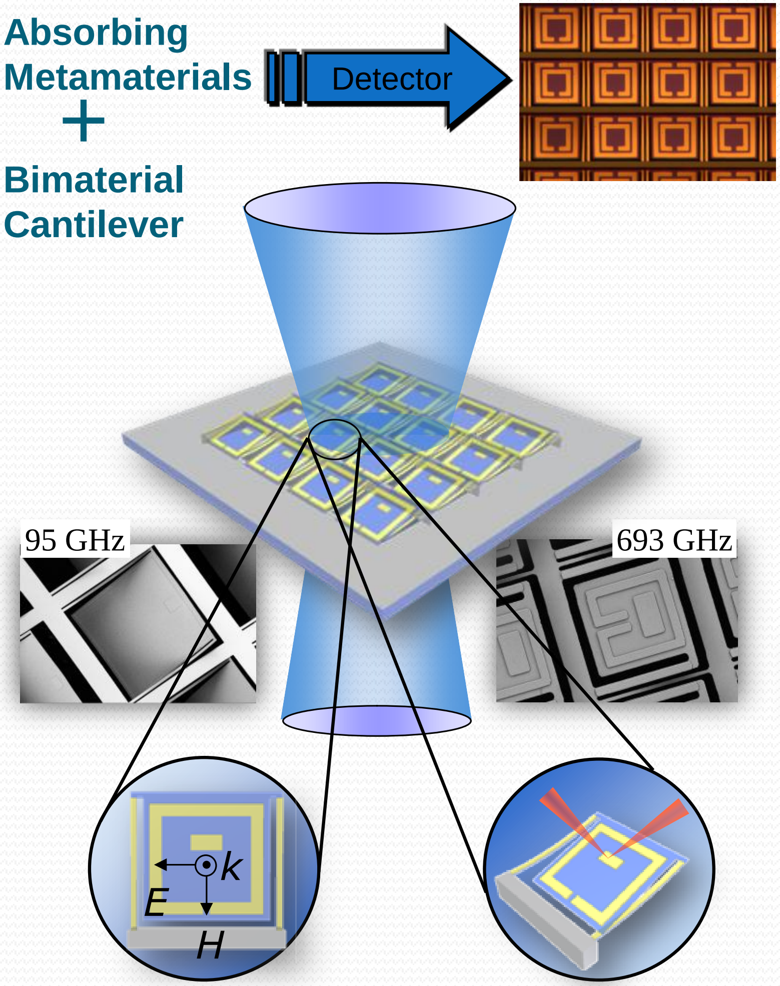
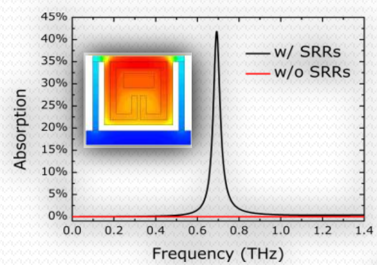
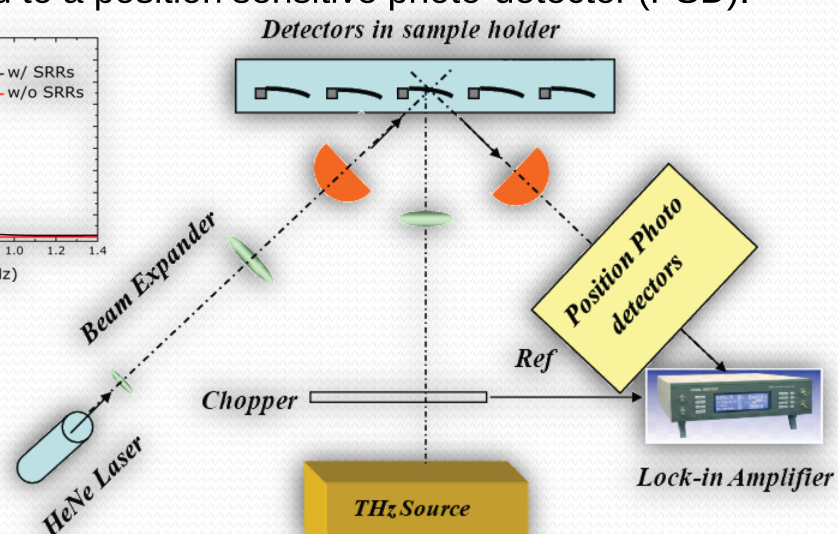
Microwave and Terahertz Wave Sensing with Metamaterials

Absorbing Metamaterials
+
Bimaterial Cantilever



- The samples are split ring resonators (SRR) fabricated on thin SiNx and supported by bi-material cantilever legs.
- The materials in the cantilever legs have different coefficients of thermal expansion, which cause the legs, and subsequently the SRR, to deflect with a change in temperature.
- This change is induced by strong absorption in the SRR upon exposure to the appropriate frequency radiation.
- To detect this deflection, a reflecting pad has been fabricated in the interior of the SRR.
- A HeNe laser beam is focused upon this pad and the reflected beam is aligned to a position sensitive photo-detector (PSD).





- Metamaterials combined with MEMS cantilever technology.
- Metamaterials are spectrally selective.
- SiNx/Au bimaterials cantilevers provide thermo-mechanical response.
- Single pixel detector scalability is wafer level design and processing.
- Metamaterial absorbers at THz frequencies are compatible with MEMS processing.

Optics Express, 19 (22), 2011

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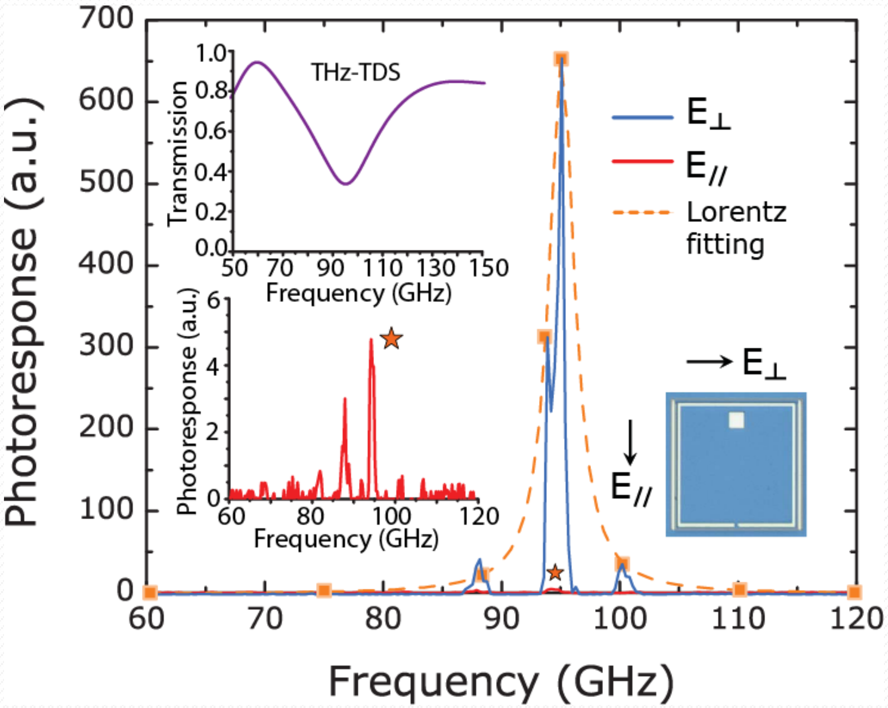
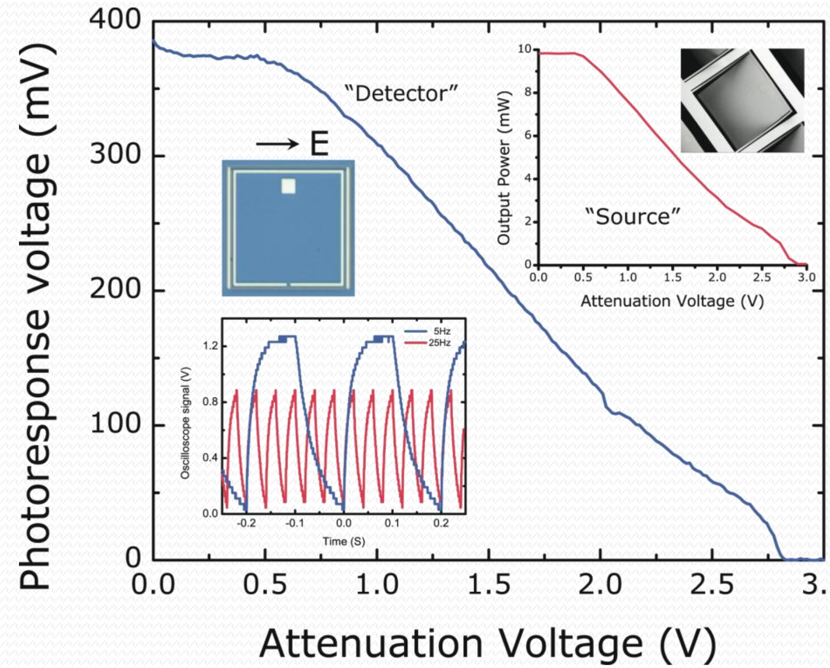
Microwave and Terahertz Wave Sensing with Metamaterials





★ Response of the 95 GHz detector as a function of frequency of the incident radiation at two polarizations. (**Inset, left top**) Transmission spectra of the detector characterized using THz-TDS with polarization of the electric field normal to the gap ($E_{\perp}$). (**Inset, left bottom**) Zoom-in view of the detector response with the polarization of the THz electric field parallel to the SRR gap ($E_{||}$). The response is two orders of magnitude smaller than the response with the polarization of the THz electric field perpendicular to the SRR gap ($E_{\perp}$).

★ Photoresponse of the 95 GHz pixel as a function of incident power. (Inset, right) SEM photo of one pixel. (Inset, left) Oscilloscope observed temporal response of the 95 GHz at 5 Hz (blue) and 25 Hz (red).

Optics Express, 19 (22), 2011

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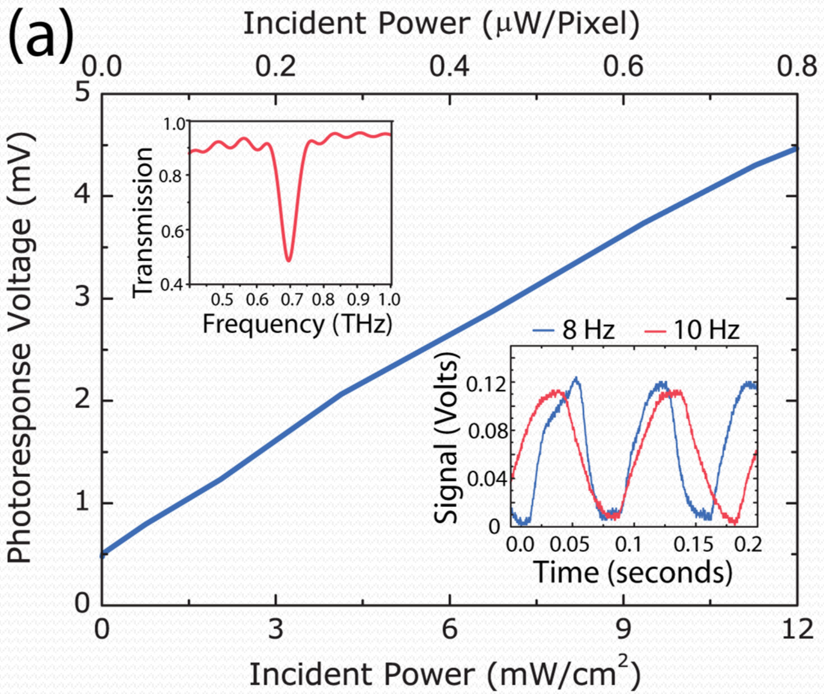
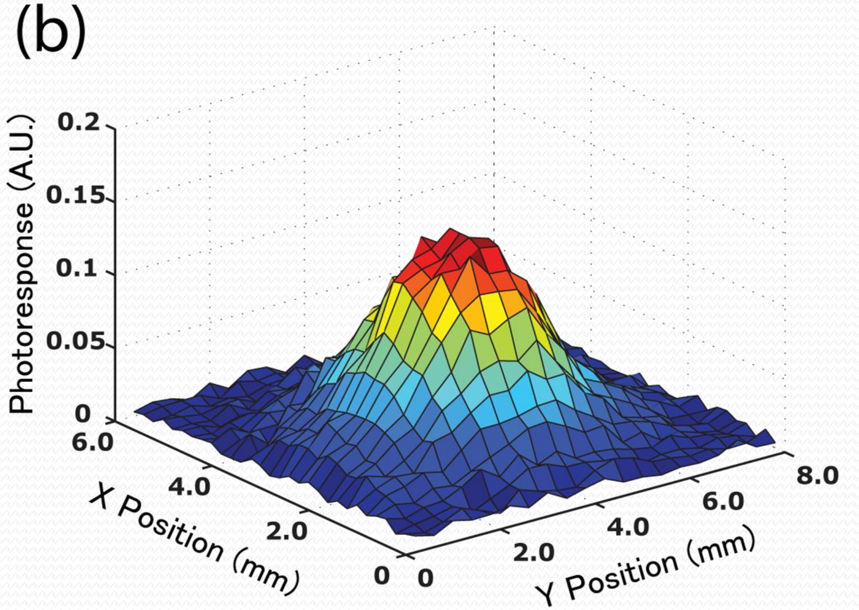
Microwave and Terahertz Wave Sensing with Metamaterials





Smaller sensor on the way?
Metamaterials to See in THz

★ Photoresponse of the 693 GHz pixel.

(a). Response of the detector as a function of incident power. The nonzero intercept results from residual vibrations. (Inset, right) Oscilloscope observed temporal responses of the 95 GHz at 8 Hz (blue) and 10 Hz (red), respectively. (Inset, left) THz-TDS characterized transmission spectrum of the detector showing a resonance at ~ 693 GHz.

(b). Image of the incident THz beam profile using the metamaterial enhanced THz detector.

Optics Express, 19 (22), 2011

Vol. 334, 18 November 2011, Science

MEMS and Metamaterials: A Perfect Marriage at Terahertz Frequencies

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MEMS and Metamaterials: A Perfect Marriage at Terahertz Frequencies

- Extremely thin metamaterial as slab waveguide at terahertz frequencies (with Koichiro Tanaka, Kyoto University; *IEEE Transactions on Terahertz Science and Technology*, 1 (2), 2011)
- Single-layer terahertz metamaterials with bulk optical constants (with Willie Padilla, Boston College; *Physical Review B*, 85 (3), 2012)
- Flexible metamaterial absorbers for stealth applications at terahertz frequencies (with Peter Jepsen, TU-Denmark; *Optics Express*, 20 (1), 2012)
- Time-resolved imaging of near-fields in THz antennas and direct quantitative measurement of field enhancements (with Keith Nelson, MIT; *Optics Express*, 20 (8), 2012)
- THz near-field Faraday imaging in hybrid metamaterials (with Paul Planken, Delft; *Optics Express*, 20 (10), 2012)
- Terahertz-field-induced insulator-to-metal transition in vanadium dioxide metamaterial (with Keith Nelson, MIT; *Nature*, 487 (7407), 2012)

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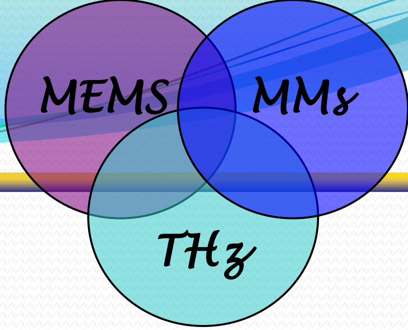
Concluding Remarks



- Metamaterials have ignited a world-wide flurry of research based in part on the realization of negative refractive index, and the idea of coordinate-transformation design of materials leading to exotic phenomena such as electromagnetic cloaking or energy concentration.
- The implementation of such ideas is exciting, but is most likely a long-term proposition in terms real-world applications.
- Briefly, metamaterials are sub-wavelength composites where the electromagnetic response originates from oscillating electrons in highly conducting metals such as gold or copper allowing for a design specific resonant response of the electrical permittivity or magnetic permeability.
- This is especially important for the technologically relevant terahertz frequency regime where there is a strong need to create components to realize applications ranging from spectroscopic identification of hazardous materials to noninvasive imaging.
- Our work has been focusing on the development of functional THz metamaterial structures and devices using MEMS technologies, which show extreme power at the micro scale level.

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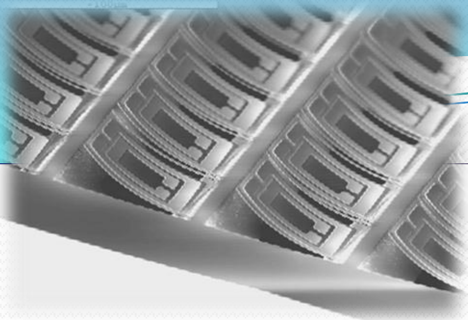

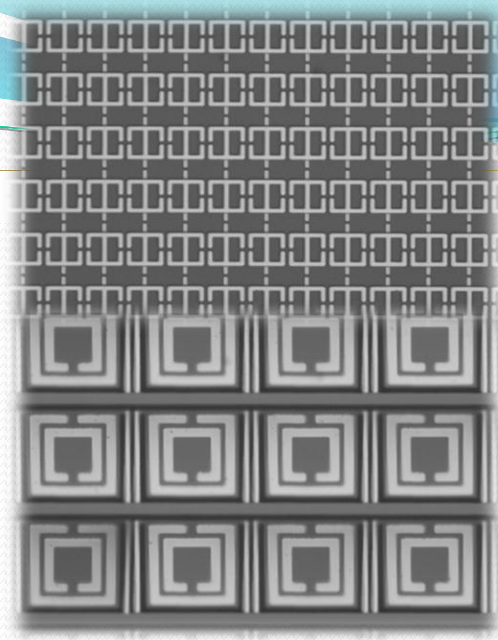
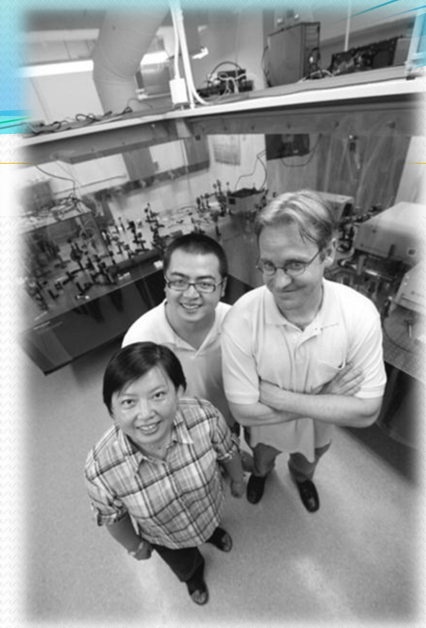


- *Nature (1)*
- *Nature Highlight (2)*
- *Science Highlight (2)*
- *Optics Express (8)*
- *Physical Review B (3)*
- *Advanced Materials (2)*
- *Journal of Physics D (2)*
- *Physical Review Letters (1)*
- *Applied Physics Letters (1)*
- *IEEE Terahertz Science & Technology (1)*
- *Journal of Micromechanics & Microengineering (1)*
- *Review Articles (2)*

Principal Investigators: Xin Zhang, Richard Averitt

Ph.D. Dissertation: Hu Tao, Andrew Strikwerda, Kebin Fan

Two Covers of Journals; Two Best PhD Dissertation Awards

Major Collaboration:
Willie Padilla (BC); Fiorenzo Omenette (Tufts); Eric Shaner (Sandia); Keith Nelson (MIT)

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